PREDICTING COST AND SCHEDULE GROWTH FOR MILITARY AND CIVIL SPACE SYSTEMS

THESIS

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AFIT/GRD/ENC/08M-01

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THESIS

Presented to the Faculty

Department of Mathematics and Statistics

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Research and Development Management

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March 2008

AFIT/GRD/ENC/08M-01

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Abstract

Military and civil space acquisitions have received much criticism for their inability to produce realistic cost and schedule estimates. This research seeks to provide space systems cost estimators with a forecasting tool for space system cost and schedule growth by identifying factors contributing to growth, quantifying the relative impact of these factors, and establishing a set of models for predicting space system cost and schedule growth. The analysis considers data from both Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) space programs.

The DoD dataset includes 21 space programs that submitted developmental Selected Acquisition Reports between 1969 and 2006. The analysis uses multiple regression to assess 22 predictor variables, finding that communications missions, ground equipment, firm-fixed price contracts, and increased program manager tenure are all predictive of lower cost growth for military space systems.

The NASA analysis includes 71 satellites and spacecraft developed between 1964 and 2004. The analysis uses a two-stage logistic and multiple regression approach to analyze 31 predictor variables finding that smaller programs (by total cost), more massive spacecraft, microgravity missions, and space physics missions are predictive of higher cost growth. For schedule growth, the study finds that larger programs and those developed by the Jet Propulsion Laboratory, Northrop Grumman, or international developers are predictive of increased schedule growth, whereas those programs developed by Johns Hopkins University are predictive of reduced schedule growth.

Acknowledgements

I would like to thank my thesis advisor, Dr. Edward White, whose enthusiasm kept me motivated through the entirety of this long project. I am extremely appreciative of his keen sense for providing the perfect balance of empowerment and instruction, which encouraged me to work diligently without ever losing sight of the big picture. I would also like to thank my committee members for their guidance and assistance with this project.

I would like to thank Warren Carlson and Donald Kehl from the Space and Missile Systems Center, for their tireless efforts to assist me in obtaining and understanding defense cost data. I would also like to thank David Graham of the NASA Cost Analysis Division and Karen Tyson of the Institute for Defense Analyses for their assistance with obtaining cost and schedule information for NASA space systems.

Finally, I would like to extend a special thank you to my husband and two kitties whose support and encouragement were critical not only to my success on this endeavor, but in everything that I do.

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PREDICTING COST AND SCHEDULE GROWTH FOR MILITARY AND CIVIL SPACE SYSTEMS

I. Introduction

Over the past decade, the United States has grown increasingly dependent on space systems in order to conduct military and civil operations. The combination of this dependence and the recent difficulties in space systems acquisition has given cause for alarm among national leaders (Allard, 2005; Defense Science, 2003). Space acquisition programs such as the Space Based Infrared System (SBIRS) High and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) have received considerable national attention (and Congressional criticism) for their excessive cost growth. For example, SBIRS High, originally estimated to cost approximately \$4 billion, is now anticipated to cost over \$10 billion. Similarly, NPOESS has almost doubled in cost growth, from an original estimate of approximately \$6 billion to current estimates of over \$11 billion (Defense, 2003a; Government, 2006). The extreme cost growth experienced by these and other military and civil space acquisition programs has led to the perception that the space acquisition process is "broken," ultimately eroding the credibility of the space acquisition community (Allard, 2005; Gourley, 2004; Lee, 2004).

This study seeks to assist cost estimators by providing the military and civil space systems acquisition communities with a set of models for predicting the likelihood and quantity of space system cost and schedule growth. These models will enable space system cost estimators to enhance their current estimating techniques as well as identify

the primary factors associated with space system cost and schedule growth. Hopefully, the creation of these models will result in better forecasting, and thus decreased future cost and schedule growth, in the acquisition of space systems.

This chapter provides an overview of this study's efforts to understand and model space system cost and schedule growth by examining the space system acquisition background, the specific research problem, the research objectives, and the methodology. The chapter concludes with an overview of the study results.

Background: Space System Acquisition

Military space system acquisition began in the 1950s with the development of ballistic missiles by the Western Development Division of the Air Research and Development Command (ARDC). In 1955, ARDC expanded its mission by taking on the responsibility of developing the Department of Defense's (DoD's) first satellite. Civil space system acquisition began in 1958 under the National Aeronautics and Space Administration (NASA) as a response to the Soviet launch of Sputnik. While the DoD focused on strategic missile development and defense satellites, NASA's role included human space flight and scientific space exploration ("Brief," 2005). Although many of the missions for the DoD and NASA overlap (such as space-based communications, weather observation, and environmental monitoring), NASA does not fall under the purview of the DoD, rather NASA operates as an Independent Agency ("Official," 2008).

In 1961, Secretary of Defense Robert McNamara gave the Air Force primary responsibility for developing all military space systems (History, 2003). In 2003, the DoD reaffirmed the Air Force's role in developing space systems when Deputy Secretary

of Defense Paul Wolfowitz designated the Secretary of the Air Force as the DoD Executive Agent for Space[1] (Department, 2003a).

The Air Force's Space and Missile Systems Center (SMC) is the current-day successor to the Western Development Division of the 1950s (History, 2003). SMC was originally aligned under the control of Air Force Materiel Command (AFMC), the Air Force's primary acquisition arm. However, in 2001, upon the recommendation of the Space Commission, SMC was realigned under the control of Air Force Space Command (AFSPC).[2] The Space Commission argues that placing SMC under AFSPC would consolidate the operational and acquisition functions for space into a single organization, thus achieving a "strong center of advocacy for space" as well as fostering an organizational climate suitable for developing space professionals (*Report*, 2001:89-90).

In addition to having a separate acquisition community for military space systems, there is also a separate process. While typical DoD acquisition follows the process outlined in the DoD Instruction 5000.1, "The Defense Acquisition System," and 5000.2, "Operation of the Defense Acquisition System,"[3] military space system acquisition follows a separate acquisition process described in National Security Space (NSS) 03-01. Through NSS 03-01, all DoD space acquisition programs follow a separate reporting chain from other DoD programs and are automatically granted waivers from DoD

[1] The National Reconnaissance Office (NRO) has responsibility for the development of reconnaissance satellites (History, 2003:1). This does not diminish the Air Force's responsibility for space systems; for, the Under Secretary of the Air Force also serves as the Director for the NRO (Department, 2003a:3).
[2] The Space Commission recommends the creation of a Space Corps within the Air Force under AFSPC as a mid term solution; in the long term, it recommends a separate military department for space (Report, 2001:89).
[3] Although Deputy Secretary of Defense Paul Wolfowitz cancelled the DoD 5000 series in 2002 (Wolfowitz, 2002), the DoD acquisition community continues to use much of this process through the discretionary use of the Defense Acquisition Guidebook, which details implementation of the DoD 5000 series (Vogel, 2003:4; "Defense," 2004).

Instruction 5000.2 (Department, 2003b; Fritchman, 2005). NSS 03-01 provides space system acquisition professionals with a flexible and streamlined process tailored towards the unique aspects of space system acquisition (Department, 2003b).

Military and civil space systems differ from other defense systems in two ways: their operational environment and their acquisition life cycle.[4] The operational environments for space systems are harsh and remote. Space systems have to deal with extremes (such as radiation, charged particles, and the vacuum of space) that land-based systems do not. Additionally, due to the remote nature of the operational environment, it is difficult to make corrections or modifications to the systems once they have been deployed. The emphasis placed on system survivability of this harsh environment results in large costs for space systems during the early stages of the acquisition life cycle. Because testing in the operational environment (space) is unrealistic, space systems acquisition places a stronger emphasis on test and evaluation during the development phase (Fritchman, 2005; Sellers et al., 2004).

In addition to the emphasis placed on the activities of the development phase, space systems also differ in their acquisition life cycle. Space systems are often acquired in small quantities and usually do not have maintenance performed on them once they become operational. Because of the limited quantities and the high development cost of space systems, their acquisition life cycle does not typically include an extensive production phase or the use of prototyping (Fritchman, 2005). As can be seen in Figure 1, a typical defense weapon system experiences the majority of its life cycle cost during

[4] The acquisition life cycle of a program includes all of the phases for developing and producing a system from the initial concept through operations and sustainment of the system ("DAU," 2007).

the operations and support phase, after the system has been deployed. Space systems, on the other hand, experience most of their costs during the system acquisition phase (Figure 2), where system design, integration, and testing occurs.

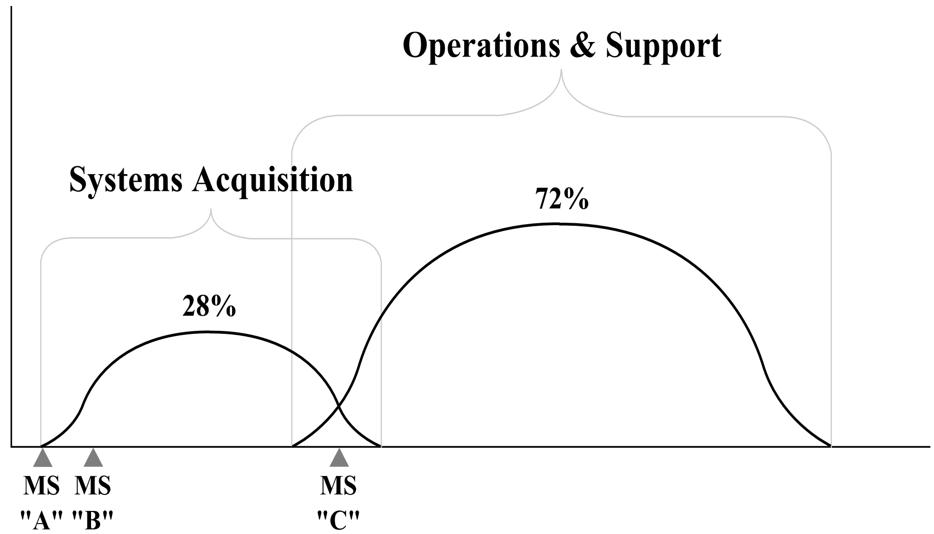


Figure 1. Typical Weapon System Life Cycle Cost Curve (adapted from Paschall, 2005)

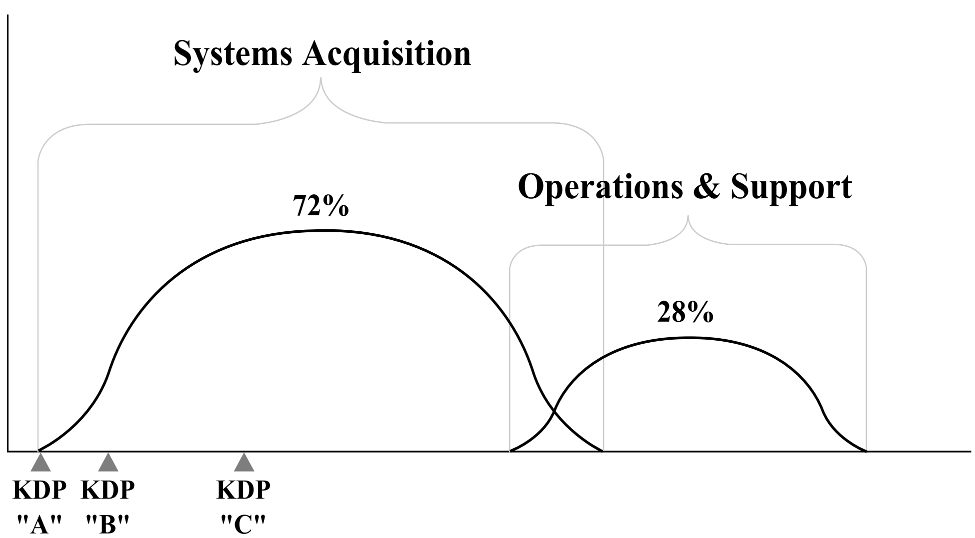


Figure 2. Typical Space System Life Cycle Cost Curve (adapted from Paschall, 2005)

NSS 03-01 accommodates the unique life cycle for space systems by offering two acquisition models: the NSS Small Quantity System Model (Figure 3) and the NSS Large Quantity Production Focused System Model (Figure 4). The NSS Small Quantity System Model is designed for programs that typically acquire ten or less units, such as satellites, ground stations, and launch vehicles. Distinctive features of this model include the Follow-on Buy Approval and the Upgrade Decision in Phase C (Figure 3). The Follow-on Buy Approval meeting occurs after the first or second unit becomes operational. During this meeting, the decision is made as to whether or not to complete the small quantity procurement. The Upgrade Decision meeting provides a forum to approve new requirements that occur after Key Decision Point C (Department, 2003b). The NSS Large Quantity Production Focused System Model applies to systems that are typically acquired in units of 50 or more. Large quantity acquisitions for space systems are primarily user equipment, such as hand-held user terminals. The NSS Large Quantity Model is similar to the life cycle model used in typical DoD acquisitions. As can be seen from Figure 4, this model includes Low-Rate Initial Production and Full-Rate Production in Phase C, which are common in standard DoD acquisitions (Department, 2003b).

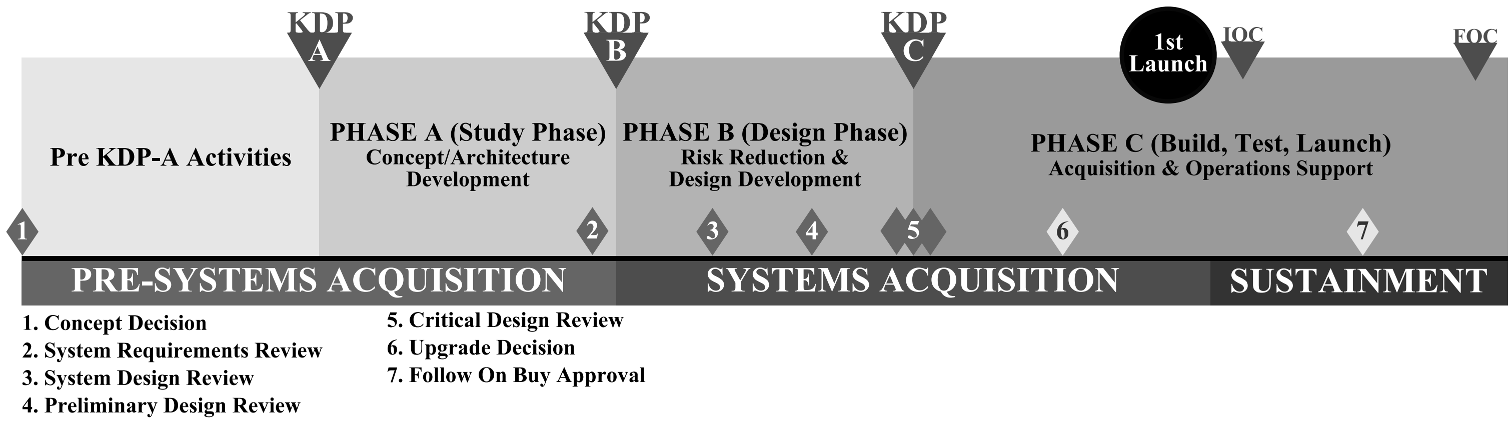


Figure 3. NSS Small Quantity System Model (adapted from Department, 2003b)

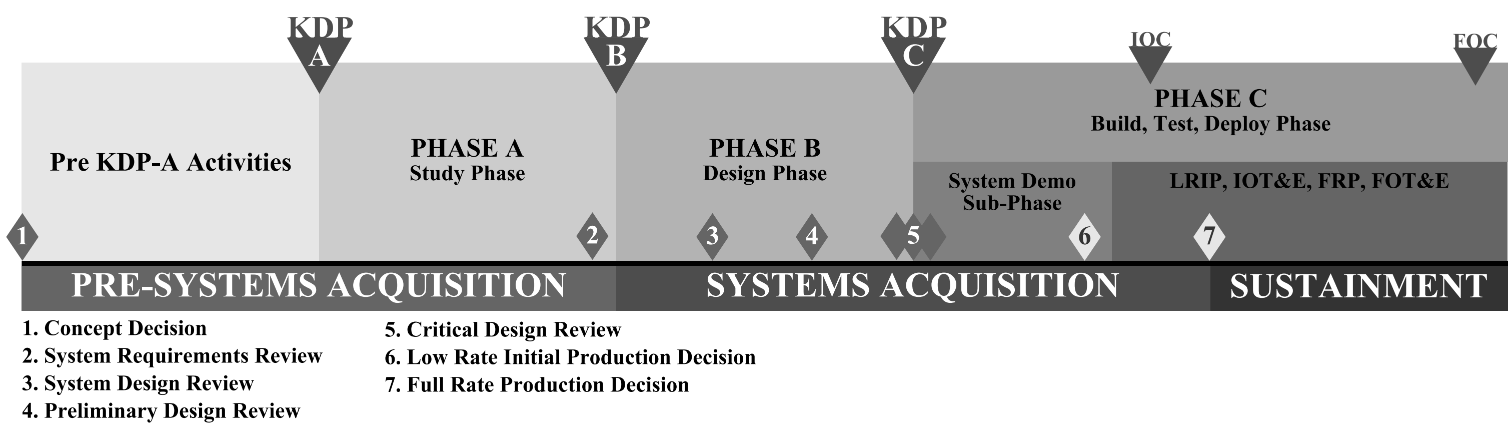
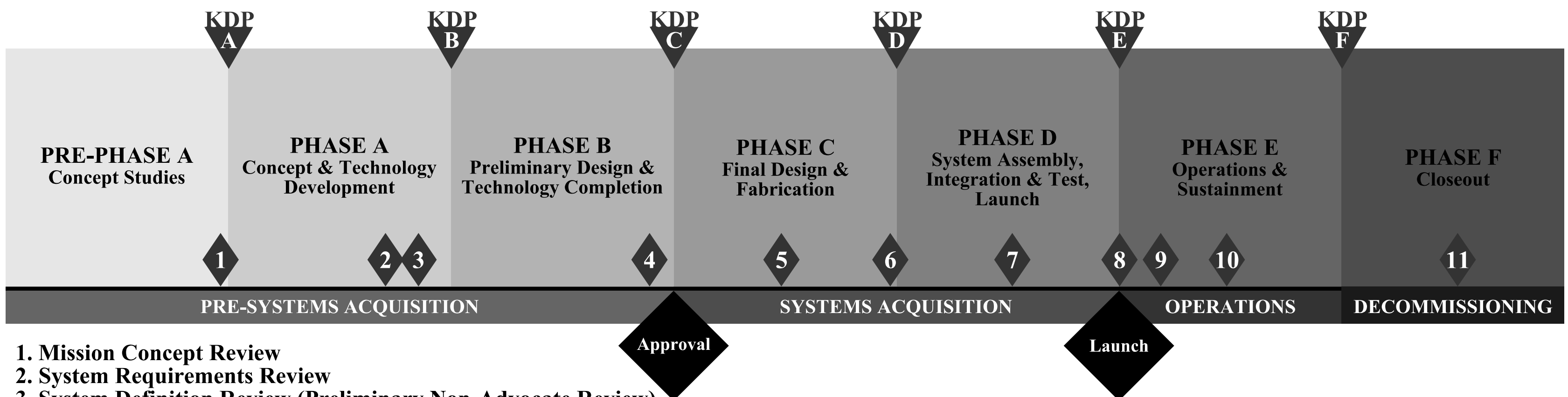


Figure 4. NSS Large Quantity Production Focused System Model (adapted from Department, 2003b)

The Government Accountability Office (GAO) notes a number of other differences between NSS 03-01 and the DoD 5000 series including the use of a Defense Space Acquisition Board (DSAB) early in the acquisition process, an emphasis on a revolutionary acquisition approach, and not requiring commitment to fully fund the program. While the Air Force claims that the use of DSABs will result in early problem identification and enable early involvement of senior leadership, the GAO argues that the DSAB will result in investment decisions being made earlier in the process, before critical technologies are mature enough to enter product development. The GAO expresses concern about NSS 03-01's practice of encouraging programs to incorporate cutting-edge technologies through a revolutionary approach; it argues that the simultaneous development of product and technology results in higher risk programs. Additionally, NSS 03-01 does not require a commitment to fully fund the program at program initiation (Milestone B), whereas other DoD acquisition programs are required to commit to full funding upon initiation. Rather, NSS 03-01 gives the DoD Space Milestone Decision Authority the flexibility to discontinue funding the program as late as the Follow-on Buy Decision, which occurs after the first few units have become operational. The GAO argues that these key differences between NSS 03-01 and traditional acquisition policy encourage space systems acquisition to take on unnecessary technical, schedule, and cost risk (Government, 2004a; Department, 2003b). The GAO's concerns about the risks in space acquisition and the ramification of these risks are not unfounded. Numerous cost, schedule, and technical problems are occurring within current space system acquisitions, causing Congress and the American public to believe that the space system acquisition process is "broken" (Tauscher, 2007; Lee, 2004).

Concerns over cost and schedule growth are not limited to the DoD; the GAO has also criticized NASA for its inability to produce realistic cost and schedule estimates. While NASA points to technical problems and funding shortages as major contributors to cost and schedule growth, the GAO finds that the problem is not a program management issue, but rather that NASA lacks a rigorous process for accurately estimating cost and schedule. NASA cost estimators lack access to sound financial and technical data, and thus are unable to produce reliable estimates (Government, 2004b).

In response to the criticisms of the GAO and other criticisms, NASA recently revamped its procedural requirements. The revised NASA Procedural Requirements, NPR 7120.5D standardizes the program life-cycle and program reviews, as well as incorporates the Key Decision Points (KDPs) found in the defense acquisition life cycle (Blythe, 2007). Figure 5 displays the acquisition life cycle found in NPR 7120.5D. In many ways, the process is similar to the DoD's space acquisition process, with heavy emphasis placed on the upfront development activities and requiring approval at each KDP in order to progress to the next phase. According to NPR 7120.5D, "NASA places significant emphasis on project formulation" (National, 2007). The emphasis on early program formulation through the number and frequency of technical and programmatic reviews appears to exceed the reviews outlined by NSS 03-01 for defense space systems. During Pre-Systems Acquisition, prior to program implementation at KDP C, NASA space systems can expect to go through four program reviews: Mission Concept Review (MCR), System Requirements Review (SRR), System Definition Review (SDR), and Preliminary Design Review (PDR). DoD space systems, on the other hand, are only subject to one review, SRR, during their Pre-Systems Acquisition Phase.



1. Mission Concept Review
2. System Requirements Review
3. System Definition Review (Preliminary Non-Advocate Review)
4. Preliminary Design Review (Non-Advocate Review)
5. Critical Design Review / Production Readiness Review
6. System Integration Review
7. Operational Readiness Review
8. Flight Readiness Review
9. Post-Launch Assessment Review
10. Critical Events Readiness Review
11. Decommissioning Review

Figure 5. NASA Space System Life Cycle (adapted from National, 2007)

Research Problem: Space System Cost and Schedule Growth

How can the military and civil space acquisition communities correct their problems of excessive cost and schedule growth? One critical step is to improve cost and schedule estimates for space systems acquisition. As with its assessment regarding NASA, the GAO finds that DoD space cost estimators are producing unrealistic estimates. In the DoD's case, space cost estimators have a tendency to make unrealistic assumptions, thus creating estimates that are highly optimistic. This underestimation of program costs leads to cost growth as the programs develop (Government, 2006).

What is wrong with optimistic cost and schedule estimates? Underestimating program costs or schedules hinders senior leadership's ability to effectively plan and make decisions. When a program's cost or schedule estimate does not reflect reality, financial planners are unable to adequately allocate the correct budgetary resources for the correct time. As a program requires more funds than were originally planned, decision makers have to respond by either reducing the quantity or performance for the system, or they have to reallocate funds from other programs in order to make up for the shortfall (Arena et al., 2006). Reallocating funds from other programs negatively impacts these programs' ability to meet their respective schedule and performance requirements. Regardless of whether decision makers choose to have the funding shortfall impact the original program or another program, the end result is that the delivered mix of capabilities will not meet those that were originally intended by strategic planners. A similar problem occurs if changes to the schedule result in funds being required at a different time than originally planned. Additionally, increases in schedule affect the capability mix by not delivering systems to the end users at the appropriate time.

Another consequence of cost and schedule growth is that it decreases the credibility of cost estimators and the space acquisition community, which can ultimately hinder space acquisition programs. United States Senator Wayne Allard (2005) expressed this sentiment at a Space Policy and Architecture Symposium:

> The Air Force and its contractors have lost all credibility with Congress when it comes to space acquisition programs. My colleagues and I are no longer surprised by additional cost increases or notices of further schedule delays. Nor do some in Congress give much credence to the Air Force's proposals to fix these programs. The Congress's lack of confidence in Air Force space acquisition management has resulted in enormous reductions in funding for space programs.

Senator Allard's comment reveals that this loss of credibility has already resulted in a Congressional response of reducing funds for space programs. Thus, in addition to funding shortfalls from underestimating costs, the space acquisition community also has to struggle with funding reductions caused by their loss in credibility.

This study seeks to mitigate these impacts of cost and schedule growth by providing space systems cost estimators with a forecasting tool for space system cost and schedule growth. In so doing, this study identifies factors contributing to space system cost and schedule growth, quantifies the relative impact of these factors, and provides a set of models for predicting space system cost and schedule growth.

Research Objectives

The purpose of this study is to answer the question, "Is it possible to create a set of models that accurately predict the likelihood and quantity of cost and schedule growth for space systems?" In order to answer this research question, this study first examines five Investigative Questions (IQs):

IQ1. Which systems should be considered "space systems"?

For the purpose of this study, which systems should be considered space systems? As discussed herein, military space system acquisition began with the Western Development Division, which was responsible for acquiring both strategic missiles and satellites. The current day space acquisition arm for the Air Force, SMC, is responsible for acquiring launch vehicles and ground equipment in addition to the satellites and land-based strategic missiles acquired by its predecessor (History, 2003). Civil space system acquisition on the other hand, focuses primarily on satellites and spacecraft. With regards to military systems should "space systems" include all of these types of systems since the space acquisition community holds the responsibility for acquiring them? Or should "space systems" refer only to those that fall under NSS Small Quantity System Model, which are similar to civil space systems?

This study chooses to include strategic missiles, launch vehicles, and ground equipment in the definition of space system. However, recognizing that strategic missiles are not being widely acquired today and that these systems do not fall under NSS 03-01, the study also opts to provide models that exclude these systems. See Chapter II for further information on space system definitions.

IQ2. What are the current methods for calculating cost and schedule growth?

By examining the current methods for calculating cost and schedule growth, this study can select an appropriate method for calculating growth. For cost growth, this investigative question includes the determination of which aspects of cost growth are important. That is, do all increases in cost qualify as cost growth? Perhaps some increases in cost do not reflect a true increase in the costs estimated for the original

program. For example, an increase in cost due to a change in the number of units procured is a change to the program itself, rather than a change to the estimated cost of the original program.

This study calculates cost and schedule growth as a percentage of the initial estimate, occurring during the development period of the space system. The calculations include quantity and inflation adjustments, where appropriate. See Chapters III and IV for further details on calculating cost and schedule growth.

IQ3. What characteristics of the program or acquisition environment are good predictors of cost and schedule growth?

In order to accurately predict cost and schedule growth, this study needs to identify characteristics of the program and acquisition environment that could be predictors of cost growth. One of the primary goals of this study is to identify the best predictors of growth and to quantitatively assess the relative impact that these predictors have on growth. The analysis examines numerous predictor variables including: commodity type, mission area, program size, and prime contractor, in order to establish a set of models for predicting space system cost and schedule growth. See Chapter III for more details on the predictor variables analyzed.

IQ4. What are the current methodologies for predicting cost and schedule growth?

Assessing the relationship between the potential predictors and cost and schedule growth requires selecting an appropriate methodology. Because this is an exploratory analysis, it is useful to review other methodologies for modeling cost and schedule growth in order to determine if this research can apply these techniques in whole or in

part. Additionally, understanding the range of methodologies available assists in revealing the strengths and limitations of the methodologies incorporated into this study.

IQ5. How can the cost and schedule growth models be validated?

By implementing model diagnostics for validating predictive models, this study is able to assess how accurately the models predict future cost and schedule growth. Validating the models ensures the robustness of the models as a predictive tool, and that the models will be useful to military and civil space system cost estimating and acquisition communities.

Methodology

Due to the difference in available data for DoD and NASA space systems, this study analyzes military and civil systems separately. The analysis of DoD space systems applies linear regression to identify predictors for military space system cost growth. Unfortunately, adequate data were not available for assessing schedule growth for military space systems.

In order to analyze NASA space systems cost and schedule growth, this study uses a two-staged regression methodology developed by Sipple (2002). The study uses this two-stage approach due to the bimodal nature of the cost and schedule growth data (see Chapter III for further details on the bimodal distribution of the data). The analysis adapts Sipple's two-staged approach by first using logistic regression in order to assess the likelihood that a NASA space system will experience high or low growth. The second stage uses multiple regression analysis in order to model the expected amount of growth. See Chapter III for further details on the methodology.

Study Results

The DoD cost growth analysis reveals that communications missions, ground equipment, firm-fixed price contracts, and increased program manager tenure are all predictive of lower cost growth.

The NASA cost growth analysis found that larger program size decreased the likelihood of being a high cost growth program, where as more massive spacecrafts and microgravity missions increased the likelihood of being a high cost growth program. For those NASA programs that are likely to experience high cost growth, the amount of cost growth increases for those programs from a space physics mission. For NASA programs in which the logistic models predict that low cost growth is likely, program start date is the best predictor of quantity of cost growth, with more recent programs associated with lower cost growth.

The NASA schedule growth analysis found that larger programs (measured in size of budget) are more likely to experience high schedule growth. For those programs likely to experience high schedule growth, the linear regressions reveal that those programs developed by JPL or an International developer (outside of the U.S.) experience a greater quantity of schedule growth. For those programs likely to experience low schedule growth, those developed by Northrop Grumman are associated with increased schedule growth, where as those space systems developed by Johns Hopkins are associated with a reduced quantity of schedule growth. See Chapters IV and V for more details on the study's results.

Organization of the Study

This chapter included an overview of the problem area, the research and investigative questions, and the methodology. Chapter II presents a literature review which begins to explore Investigative Questions 1-4 on defining space systems, calculating cost growth, identifying potential predictors of cost growth, and identifying methodologies for prediction cost growth. Chapter III provides a detailed discussion on the data and methodology, concluding the discussion on Investigative Questions 1-4, as well as addressing Investigative Question 5 on validation methods. Chapter IV details the preliminary, logistic, and multiple regression analysis of the data, as well as detailing the diagnostic tools used for validating the models. Chapter V concludes the study with a discussion of the results.

II. Literature Review

Chapter Overview

This literature review examines previous acquisition cost and schedule growth studies in order to gain a greater understanding of space system cost and schedule growth and how best to analyze it. In so doing, this chapter begins the study's exploration of four of the investigative questions introduced in Chapter I:

1. Which systems should be considered "space systems"?
2. What are the current methods for calculating cost and schedule growth?
3. What characteristics of the program or acquisition environment are good predictors of cost and schedule growth?
4. What are the current methodologies for predicting cost and schedule growth?

This literature review examines these four investigative questions by establishing the scope of the literature, identifying definitions for "space system," detailing methods for calculating cost and schedule growth, discussing candidate predictor variables, and evaluating past methodologies.

Literature Scope

As discussed in Chapter I, this study focuses on cost and schedule growth for military and civil space systems. Due to the limited number of space system cost and schedule growth studies, this literature review also considers research focusing on acquisition of all types of Major Defense Acquisition Programs (MDAPs).[5] Recent

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[5] Major Defense Acquisition Programs (MDAPs) are defense programs that have an estimated Research, Development, Test and Evaluation (RDT&E) cost of over $365 million or an estimated Procurement cost of more than $2.19 billion. Additionally, high interest programs not meeting these requirements can be designated as MDAPs by the Under Secretary of Defense for Acquisition, Technology, and Logistics USD(AT&L) ("Life," 2004).

studies analyzing space system cost growth are primarily qualitative (Defense Science, 2003; Salas, 2004; Government, 2006). Although the space acquisition community has placed considerable effort in modeling *cost* (Bearden, 2000/2001; Tieu et al., 2000), there is a dearth of quantitative analysis on space system *cost growth*. Recent quantitative studies on space system cost growth appear to be limited to two NASA studies: Tyson et al.'s (1992a) and Schaffer's (2004).

However, cost growth studies examining all MDAPs have been plentiful. Most of these studies use Selected Acquisition Reports (SARs) (which contain program costs and cost estimates) as their source for cost data. All MDAPs are required to submit SARs to Congress annually, with "exception SARs" submitted on a quarterly basis if major changes occur (Hough, 1992). Most DoD cost growth studies use SAR data to examine weapon system cost growth across multiple services and multiple platforms. These studies may include cost growth data for space systems; however, these studies do not conduct separate analyses on the relationship between predictors of cost growth and space system cost growth.

Cost growth literature for defense programs and space systems far exceeds the available literature for schedule growth. There are many possible reasons for the limited number of schedule growth studies. Cashman (1995) identifies attitudes regarding lack of control over schedule and beliefs that schedule growth on one program does not translate to other programs as the reasons for limited research. Cross (2006) points out other limitations, especially when using SAR data, including minimal reporting requirements and inconsistencies in schedule baselines. Quantitative schedule growth

studies examine all defense weapons systems; there do not appear to be any focused solely on space systems.

DoD cost and schedule growth studies referenced in this literature review include, but are not limited to, studies performed by the RAND Corporation, Institute for Defense Analyses (IDA), Management Consulting and Research (MCR), Air Force Institute of Technology (AFIT) students, Naval Postgraduate School (NPS) students, and the Office of the Secretary of Defense (OSD) Cost Analysis Improvement Group (CAIG). The DoD cost and schedule growth studies conducted by RAND and IDA consist of a series of analyses performed in the early 1990s (Drezner et al., 1993; Tyson et al., 1992b, Drezner and Smith, 1990), as well as a follow-on series performed in the mid-2000s (Arena et al., 2006; McNicol, 2005). Both the current and historical RAND and IDA cost and schedule growth studies primarily center on descriptive statistics.[6]

In addition to the recent RAND and IDA cost and schedule growth studies, a series of AFIT theses analyze DoD weapon system cost and schedule growth. Unlike the RAND and IDA studies, the AFIT theses employ more rigorous statistical methods, such as logistic and multiple regression analysis. These statistical techniques model cost and schedule growth, thus enabling the researcher to make predictions regarding cost and schedule growth for systems not included in the sample. Another key difference is that the AFIT theses examine subsets of total cost growth, for example, schedule or engineering changes (Foreman, 2007; Cross, 2006; Monaco, 2005; Genest, 2004; Lucas, 2004; McDaniel, 2004; Rossetti, 2004; Bielecki, 2003; Moore, 2003; Sipple, 2002).

[6] Descriptive statistics employ visual methods in order to summarize the characteristics of the data in the sample, as opposed to inferential statistics which use the data to make predictions about the population from which the sample was drawn (McClave et al., 2005:5)

Defining "Space System"

In order to analyze space system cost and schedule growth, this study must consider Investigative Question 1, "Which systems should be considered 'space systems'?" Tyson et al., in their study on NASA and DoD space systems, define a space system as "a collection of integrated components to achieve a specific purpose beyond the Earth's atmosphere, such as Earth observation or planetary exploration" (1992a:4). From this definition, those systems operating in the space environment ought to be considered space systems. Thus, satellites and non-orbiting spacecraft are clearly space systems. But what about systems designed to support these missions, such as launch vehicles or satellite terminals? Are they not also "space systems"?

Sellers et al. (2004), in *Understanding Space*,[7] describe the space mission architecture as being composed of six parts: the mission, the spacecraft, the trajectories and orbits, the launch vehicle, the mission operations systems, and the mission management and operations. This interpretation is considerably broader than Tyson et al.'s (1992a) by including the associated launch vehicles and infrastructure.

Another approach to defining "space system" is to examine which systems are operated and acquired by the space segments of the DoD. Air Force Space Command (AFSPC) operates all space forces for the Air Force. AFSPC operations involve the control of space-based satellites, ground-based terminals and early warning radars, and strategic missiles. The Space and Missile Systems Center (SMC) is the acquisition arm for AFSPC and is the primary acquirer for DoD space systems ("Air," 2007). SMC

[7] The *Understanding Space* textbook is widely used in Air Force space education, including courses taught at the Air Force Academy, the Air Force Institute of Technology, and the Space and Missile Systems Center.

acquires satellite systems, launch vehicles, land-based ballistic missiles, and space system ground equipment (History, 2003). Thus, from the current DoD perspective, space system operations and acquisition not only includes all of the systems provided in Sellers et al.'s (2004) interpretation, but also includes strategic missiles. Similar to the Air Force, the Army consolidates its missile acquisition and operations with its other space system acquisition and operations under a single organization, the U.S. Army Space and Missile Defense Command ("U.S.," 2007).

How have other cost and schedule growth studies defined "space systems"? Unfortunately, most DoD studies avoid defining "space system" when referring to weapon system types, choosing instead to segment these types of systems into separate categories such as "satellites," "launch vehicles," and "missiles" (Arena et al., 2006; Tyson et al., 1992b; Wolf, 1990). As for the limited number of DoD studies that reference space systems, satellites and launch vehicles are consistently treated as space systems, while strategic missile systems vary. McCrillis (2003) separates strategic missiles from tactical missiles, choosing to include strategic missile systems in the space category. Drezner et al. (1993) combine strategic missiles with tactical missiles into a single "missile" category.

Cost and Schedule Growth Definition and Calculation

In addition to exploring the possible definitions for "space system," this study must also Investigative Question 2, "What are the current methods for calculating cost and schedule growth?" This section first examines cost growth, which includes three main elements: the cost growth formula, the variance types, and the inflation and quantity

adjustments. This section concludes with an examination of schedule growth calculations.

Cost Growth Formula

Cost growth is a comparison of cost variance to the original cost estimate. Cost variance is defined as the difference between planned cost (original baseline cost estimate) and actual cost (or updated cost estimate) (Department, 1980). Cost growth studies calculate cost growth in one of two ways. The first approach is to calculate cost growth as a percentage of the original cost estimate (McNichols and McKinney, 1981; Pannell, 1994; Bielecki and White, 2005):

$$\text{Cost Growth} = \frac{\text{(Actual-Estimate)}}{\text{Estimate}} \tag{1}$$

Equation 1 provides cost growth as a percentage, where a value of "zero" means the is no cost growth, a negative value means that the actual cost is less than the planned costs, and a positive value means that the actual cost is greater than the planned cost.

The second approach is to calculate cost growth as a cost growth factor (CGF) or cost growth ratio (CGR). This approach simply divides the actual cost (or updated cost estimate) into the planned cost (Arena et al., 2006; McCrillis, 2003; Tyson et al., 1994; Drezner et al., 1993):

$$\text{Cost Growth} = \frac{\text{(Actual)}}{\text{Estimate}} \tag{2}$$

Equation 2 provides cost growth as a factor, where a value equal to one means there is no cost growth, a value less than one means that the actual cost is less than the planned cost, and a value greater than one means that the actual cost is greater than the planned cost.

In addition to identifying approaches to calculate cost growth, one must also define the components of the cost growth formula: estimated cost and actual cost. DoD cost growth studies typically use the Development Estimate (DE), which is the estimate submitted for Milestone B, as the baseline estimate.[8] The DE is the best estimate to capture the program's planned cost because at this point the major design and capability trade-offs have occurred and the program office is ready to begin system development ("Defense Acquisition," 2007; Jarvaise et al., 1996; Department, 1980).

While cost growth studies agree on which estimate to use as the baseline cost, there is some variation in which estimate to use as the actual cost. A number of studies use the current estimate as actual cost (McCrillis, 2003; Drezner et al., 1993; McNichols and McKinney, 1981). By using the current estimate, not all programs will be at the same stage in their development; some programs will be in the beginning of their development, some programs will be near the end of their development, and some may even be complete. Those programs that are near the end of development or are complete will have incurred a higher proportion of their cost growth than those at the beginning. Basing calculations on programs at different stages of development may cause those at the beginning of their development process to bias the results because they have not yet experienced most of their cost growth. Arena et al. (2006) show that programs continue

[8] Milestone B, previously known as Milestone II, marks program initiation and is the point where a DoD weapon system enters System Development and Demonstration.

to incur cost growth until approximately 70-80% of their development and production has been completed. Because of this tendency to incur cost growth through the later stages of development and production, Arena et al. (2006) choose to include only completed programs; therefore, their analysis consists of only final system costs.

Most DoD cost growth studies, however, use a mix of completed and on-going programs. McNicol (2005) sets a minimum requirement for programs to be at least three years past Milestone B to qualify for inclusion in his cost growth study. Other researchers place a limit on the time frame by using costs from Milestone B up to the initial operational capability (IOC) date, but do not include costs occurring after IOC (Tyson et al., 1992b; Wolf, 1990).

Variance Types

As previously mentioned, most DoD cost growth studies use SARs as their source for cost data. SARs include the original DE and current estimates (CE). Differences between the DE and the CE are called “variances” and are separated into seven categories: Economic, Quantity, Schedule, Engineering, Estimating, Support, and Other (Hough, 1992; Department, 1980). See Chapter III for a more detailed discussion of the SAR.

Most studies agree that variances due to inflation (Economic category) or quantity constitute unforeseen cost growth, and thus choose to adjust either the DE or the CE for these types of cost growth (see section on Inflation and Quantity Adjustments). RAND, IDA, AFIT, and NPS studies typically combine the other five cost variances (Engineering, Schedule, Support, Estimating, and Other), focusing on total cost growth adjusted for quantity and inflation (Arena et al., 2006; Drezner et al., 1993; Tyson et al.,

1994; Tyson et al., 1992b; Moore, 2003; Genest, 2004; Lucas, 2004; Wolf, 1990). Fast (2007), in "Sources of Program Cost Growth," argues that because Quantity, Economic, Estimating, and Other variances represent changes that are beyond the cost estimator's ability to forecast, these categories do not constitute actual cost growth; rather, it is the combination of Engineering, Schedule, and Support that constitutes actual cost growth. DoD cost growth studies examining total cost growth have yet to adopt this recommendation to exclude the Estimating and Other categories and focus solely on the combination of Engineering, Schedule, and Support.

Instead of considering total cost growth, several AFIT theses examine these categories separately in order to isolate the predictors for these individual aspects of cost growth. Sipple (2002) examines cost growth due to Engineering varinaces within the Research, Development, Test, and Evaluation (RDT&E) appropriation. Bielecki (2003) builds on this work by individually examining the RDT&E appropriation for the four other categories: Estimating, Schedule, Support, and Other. Rossetti (2004) complements both sets of work by examining the Estimating and Support categories for the Procurement appropriation, whereas McDaniel (2004) analyzes the Engineering and Schedule categories for the Procurement appropriation.

Although using SAR variance categories is the primary method for analyzing cost growth, several studies use the variance categories created by the DoD Office of the Director for Program Analysis and Evaluation (PA&E). PA&E uses SAR data to create its own cost database, dividing variances between those that are attributed to mistakes and those that are attributed to decisions. The mistake variance is further divided into five subcategories: production, development and engineering, logistics support, schedule

and management factors, and other. Similarly, the decision variance is divided into five subcategories: requirements, schedule, logistics support, external factors, and other. IDA, CAIG, and NPS have taken advantage of this database in order to characterize cost variances attributable to decisions and mistakes (McNicol, 2005; McCrillis, 2003; Pannell, 1994).

Inflation and Quantity Adjustments

DoD cost growth studies use one of two methods to adjust for inflation: 1) convert all program costs to base-year dollars for that system or 2) adjust costs for all programs to a standard base year. Most studies, including those done by RAND, IDA, and MCR, use base-year dollars to adjust for inflation when calculating cost growth (Arena et al., 2006; Drezner et al., 1993; Tyson et al., 1992b; McNichols and McKinney, 1981). Recent studies using the PA&E database adjust for inflation by converting all program cost data to Fiscal Year (FY) 2000 constant dollars (McNicol, 2005; McCrillis, 2003). AFIT theses take a similar approach, converting base-year dollars for each program into a standard base year (Lucas, 2004; Bielecki, 2003; Sipple, 2002).

In addition to adjusting for inflation, DoD cost growth studies also adjust for variances due to quantity changes because cost estimators create the DE with the original planned quantity in mind and do not incorporate adjustments for quantity changes. To adjust for quantity, DoD cost growth studies take one of two approaches: 1) adjust the CE to reflect baseline quantities or 2) adjust the DE to reflect current/final quantities. Adjusting the CE to reflect baseline quantities provides cost growth in terms of the initial cost estimate and prevents a “floating baseline,” where the quantity used for calculations changes from year to year (Drezner et al., 1993). On the other hand, adjusting the DE to

reflect current quantities allows the researcher to modify estimates while keeping actual costs intact. When calculating total cost growth with both RDT&E and Procurement appropriations, adjusting the DE to the current quantity maintains the proportion of procurement cost to total cost (Arena et al., 2006).

After selecting whether to use the baseline or current quantity, the researcher must then make the necessary adjustments to the CE or DE. Hough (1992) offers three methods for performing this quantity normalization:

1. Normalize using variance listed in the SAR Quantity category only,
2. Normalize using cost-quantity curves, thus adjusting all variances that occur at other than baseline quantities, or
3. Normalize using a hybrid approach by adjusting for quantity-related variances (both those listed in SAR Quantity category as well as those listed in other categories but described as quantity-related in the narrative portion of the SAR) and then adjusting the remaining variance using cost-quantity curves.

Although Hough (1992) recommends using either cost-quantity curves or the hybrid approach, most AFIT theses implement the first approach and exclude cost variances listed in the Quantity category (Genest, 2004; Bielecki, 2003; Sipple, 2002). One exception is Abate's (2004) thesis on missile system cost growth which uses the hybrid approach. DoD cost growth studies performed by RAND, IDA, and CAIG implement cost-quantity curves (also known as learning curves, cost improvement curves, or price improvement curves) either directly or through the hybrid approach (Arena et al., 2006; McNicol, 2005; McCrillis, 2003; Drezner et al., 1993; Tyson et al., 1992b).

Calculating Schedule Growth

As with cost growth, schedule growth is most commonly calculated either as a percentage of the planned length or as a ratio between actual and planned length (Foreman, 2007; Cross, 2006; Monaco, 2005; Wolf, 1990). Other methods for calculating schedule growth include measuring just the raw increase in length in terms of how much the actual length exceeded the planned length (Drezner and Smith, 1990). In addition to measuring schedule growth in terms of length, Cashman (1995) also provides calculations for schedule growth in dollar terms and in frequency of schedule changes.

Predictor Variables

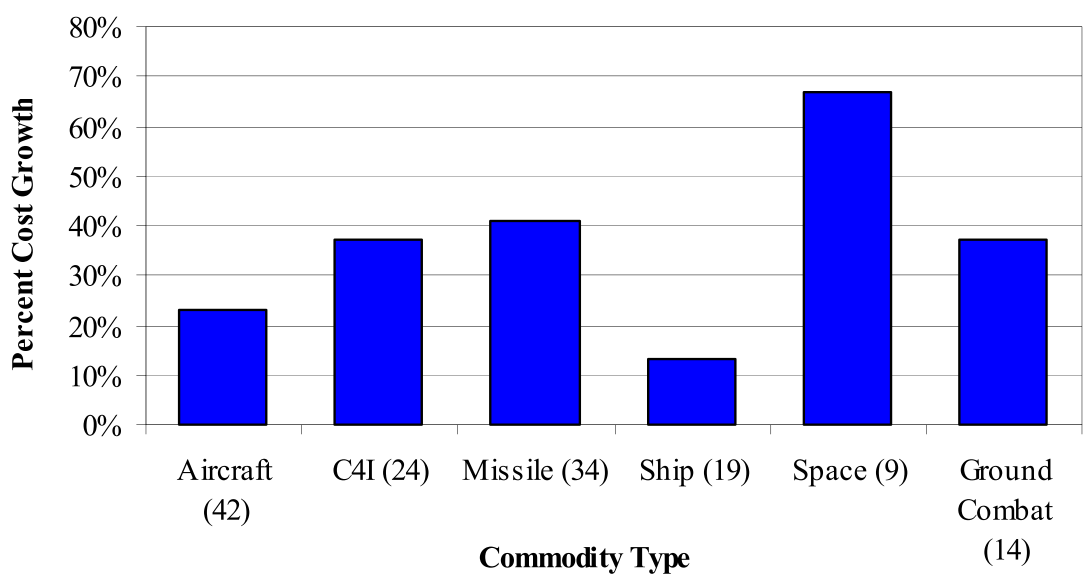
In addition to presenting methods for calculating the response variable (cost or schedule growth), the literature reveals an array of possible predictor variables to assist in answering Investigative Question 3, "What characteristics of the program or acquisition environment are good predictors of cost and schedule growth?" This discussion begins by reviewing quantitative DoD cost growth studies for predictors of cost and schedule growth, which are grouped into three categories: program attributes, management practices and acquisition strategies, and external factors. The discussion concludes with an examination of predictors identified by qualitative studies focused exclusively on space systems.

Program Attributes

Cost and schedule growth studies compare a variety of program attributes, in order to identify those program attributes that consistently correspond with high or low growth. The primary program attributes associated with cost growth are commodity type and program size, whereas the primary characteristic associated with schedule growth is

program volatility. Both cost growth and schedule growth studies identify degree of technical difficulty as a predictor of growth.

Commodity Type. A number of studies compare cost growth across commodity types, such as aircraft, ships, land vehicles, and missiles. As discussed herein, there is some differentiation on the commodity classification; for example, some researchers choose to place satellites, launch vehicles, and strategic missiles into separate commodity classes (Arena et al., 2006) while others choose to combine these into a single space commodity class (McCrillis, 2003). Studies that consider space as a single commodity class consistently find space systems to be associated with higher cost growth (McDaniel, 2004:83-97; Rossetti, 2004:93-99; McCrillis, 2003). As seen in Figure 6, space systems experience considerably greater total cost growth than other types of DoD programs.



Note: Numbers in parentheses are numbers of programs.

Figure 6. Total Program Cost Growth by Commodity (McCrillis, 2003)

Program Size. When considering program size, cost growth studies consistently find that smaller programs (that is, lower cost programs) have higher cost growth than larger programs (McCrillis, 2003; Dameron et al., 2002; Pannell, 1994; Drezner et al., 1993). As seen in Figure 7, programs with Milestone II estimates (DEs) greater than $10 billion are unlikely to experience more than 50% cost growth, whereas a number of systems with estimates below $10 billion have experienced greater than 50% cost growth. Drezner et al. (1993) offer three possible explanations for smaller programs incurring high cost growth: 1) oversight is often less for smaller programs, 2) equivalent increases in cost are proportionally greater for smaller programs, and 3) R&D costs (which tend to have higher cost growth than procurement costs) consist of a greater proportion of the total cost for smaller programs. While Tyson et al. (1992a) find this relationship to be the case for DoD space programs, they observe that NASA space programs are the opposite, with larger NASA programs experiencing higher cost growth. However, a more recent study of NASA programs contradicts this conclusion, finding that both NASA and DoD programs experience lower cost growth as program size increases (Schaffer, 2004).

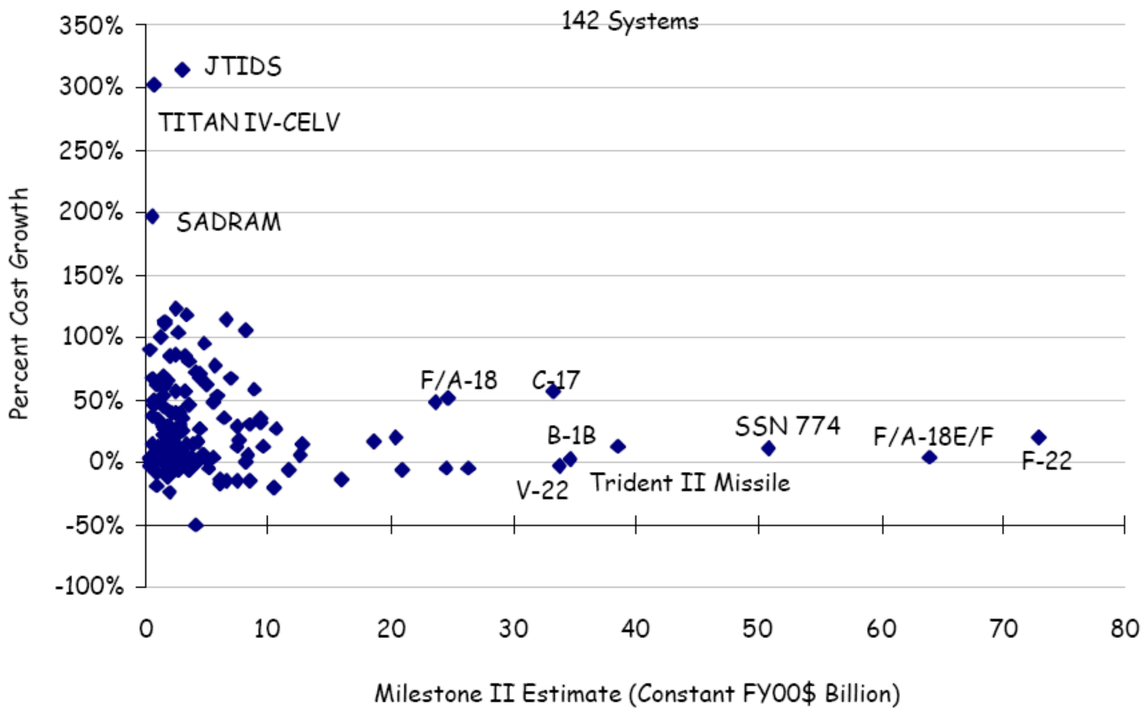


Figure 7. Total Cost Growth by Program Size (McCrillis, 2003)

Program Volatility. DoD schedule growth studies find that volatility is one of the main factors associated with higher schedule growth. These studies measure volatility in a variety of ways including the number of changes to the original estimate (Foreman, 2007; Cross, 2006), funding instability (Foreman, 2007; Drezner and Smith, 1990), technical problems, and design changes (Cashman, 1995; Drezner and Smith, 1990).

Technical Difficulty. DoD cost and schedule growth studies evaluate the degree of technical difficulty by comparing cost or schedule growth of new programs to those that have predecessor programs. One would expect that new programs would be more technically challenging (and thus have higher cost or schedule growth) than modification programs that build upon predecessor programs. Drezner et al. (1993) find that modification programs experience lower average total cost and lower cost growth, as

shown in Table 1. Other studies also consistently show this scenario to be the case, with new programs having higher cost or schedule growth than modification programs (Cross, 2006; McNicol, 2005; Monaco, 2005; Tyson et al., 1992b).

Table 1. Modifications Versus New Programs (Drezner et al., 1993)

	Cost Growth Factor	**Number of Observations**	**Average Program Cost (billions, FY90$)**	**Average Age (years past EMD)**
Modification	1.16	36	4.0	8.9
New Start	1.21	84	6.1	9.7

Management Practices and Acquisition Strategies

DoD cost and schedule growth studies also examine the impact of management practices and acquisition strategies on growth. These practices and strategies include acquiring service, schedule characteristics, contract type, and prototyping.

Acquiring Service. DoD cost growth studies disagree on the impact of service type on cost growth. In their study for MCR, McNichols and McKinney (1981) find that the Army tends to have higher cost growth than the other services. This finding is confirmed by a RAND study in 1993 (Drezner et al., 1993) and more recently by an IDA study in 2005 (McNicol, 2005). Recent AFIT theses, on the other hand, are mixed with some finding Navy involvement to be associated with higher cost growth (McDaniel, 2004), while others find Navy involvement to be associated with lower cost growth (Rossetti, 2004; Bielecki, 2003). To further confound these results, a number of studies have found that there is no difference in cost growth among services (Arena et al., 2006;

Pannell, 1994). Pannell (1994) explains that studies relying on data from the early 1980s are likely to find Army programs experiencing high cost growth because the Army was going though its modernization program. He suggests that more recent data reflect the completion of Army modernization and that the Army is now better able to control program costs. Drezner et al. (1993) explain that Army programs are more likely to have higher cost growth because the Army programs in their dataset tend to be smaller and older than the Navy and Air Force programs. Thus, some of the cost growth attributed to service may actually be due to size and age.

Schedule Characteristics. AFIT theses find that schedule characteristics, such as the length of the Research and Development (R&D) Phase or the length of the Production Phase, are good indicators of both the likelihood of cost growth and the amount of cost growth. The most consistent finding is a positive relationship between the length of the R&D phase and cost growth; that is, longer R&D phases correspond with increased cost growth (Lucas, 2004; McDaniel, 2004; Bielecki, 2003; Sipple, 2002). AFIT studies find lower schedule growth for programs with a Phase A, programs that have a longer Phase A plus planned Phase B, and for programs that have their Milestone C prior to their Initial Operational Capability (IOC) date (Foreman, 2007; Cross, 2006; Monaco, 2005).

Contract Type. As for acquisition strategies, IDA finds that multi-year procurement contracts and development contracts that include incentives tend to have lower cost growth (Tyson et al., 1992b). McNicol (2005) finds that total package procurement contracts result in higher cost growth, and Rossetti (2004) finds that fixed-price contracts decrease the likelihood of cost growth occurring.

Prototyping. The literature is mixed on the impact of prototyping on cost growth. IDA finds prototyping to be an effective tool for reducing cost growth (Tyson et al., 1992b); however, RAND finds that programs with prototyping experience higher cost growth (Drezner et al., 1993).

External Factors

External factors impacting cost and schedule growth include acquisition reform, political party, and external guidance. In Abate's (2004) study on the impact of acquisition reform on cost growth of tactical missiles, he finds that missile systems reporting their Milestone B estimate during the post-acquisition reform period (1997-2001) experience higher cost growth than those reporting in the pre-acquisition reform period (1991-1996). In Wolf's (1990) study on political impacts on cost and schedule growth, he finds that both cost and schedule growth are higher for programs that are initiated during times when the Democratic Party has a strong majority in Congress. Gounatidis (2006) finds that a Democratic President correlates with reduced cost overruns for that year.[9] In addition, Gounatidis (2006) finds that having the same political party control both houses of Congress or having the same political party control the Senate and Presidency correlates with increased cost overruns for that year. In their study on schedule growth, Drezner and Smith (1990) find that external guidance such as oversight reviews, legislation, and directives are associated with higher schedule growth.

[9] Instead of evaluating SAR data for total program cost growth, Gounatidis examines annual cost growth reported in Cost Performance Reports (2006:43).

Predictors from Space Studies

In addition to the quantitative DoD cost and schedule growth studies, several agencies have conducted qualitative analyses on cost growth among space systems. These qualitative studies agree that the main contributors to space system cost growth are: the increase in system requirements (requirements creep), the large number of Key Performance Parameters (KPPs), the short tenure of program managers (PMs), the lack of systems engineering expertise, the use of compressed schedules, the incorporation of immature technologies, and the use of Total System Performance Responsibility (TSPR) contracts (Defense Science, 2003; Government, 2006; Salas, 2004).

From these findings on predictors of cost growth, a disparity has emerged; while several of the factors identified by these qualitative studies (such as contract type and schedule characteristics) appear in the quantitative studies, most of the factors do not. What could be the cause of this disconnect? Many of the quantitative studies take advantage of the data collected in the SAR, which limits their pool of predictor variables to those provided in the SAR. Additionally, the predictors identified in the qualitative studies may be difficult to operationalize (that is, difficult to measure), such as systems engineering expertise. However, many of the factors operationalize rather easily, such as the number of KPPs, the number (or growth) in requirements, the average tenure for PMs, and the maturity of technology.[10] In these cases, data availability is most likely the reason that quantitative studies fail to incorporate these factors into their analyses.

[10] The DoD uses a standard system to rate technology maturity, known as Technology Readiness Levels (TRLs) (Department, 2005).

Methodologies

The literature review now turns to Investigative Question 4, "What are the current methodologies for predicting cost and schedule growth?" The investigation provides valuable insight into understanding the variety of techniques employed by cost and schedule growth studies, which include case studies, graphical analyses, and regression analyses.

Case Studies

In order to assess the state of acquisition for national security space programs, the Defense Science Board Task Force, led by Thomas Young, employs a qualitative approach. The Young Task Force mainly relies upon interviews with government personnel, retired government personnel, and contractors. Its interviews span a broad range of the acquisition spectrum: high-level decision makers from the Pentagon and AFSPC responsible for strategic planning; acquirers from SMC responsible for implementing daily acquisition duties; and contractors from Boeing Company, Lockheed Martin, and TRW responsible for designing and building space systems (Defense Science, 2003). The Task Force augments its study with a more detailed examination of three high profile space systems: Space-Based Infrared System (SBIRS) High, Future Imagery Architecture (FIA), and Evolved Expendable Launch Vehicle (EELV) (Defense Science, 2003).

In its 2006 report on space system cost estimates, the Government Accountability Office (GAO) utilizes a case study methodology involving detailed interviews with program office and contractor personnel as well as the examination of documentation on program cost and other program aspects. In this study, GAO focuses on six programs:

Advanced Extremely High Frequency (AEHF) satellite, EELV, Global Positioning System (GPS) IIF, National Polar-orbiting Operational Environmental Satellite System (NPOESS), SBIRS High, and Wideband Gapfiller Satellite (Government, 2006).

One of the main benefits of a case study is the ability to gain a depth of understanding of the particular program(s) being examined. However, case studies are time consuming, costly, and limited by small sample size. Additionally, they do not provide a quantitative measure of the relative contribution the predictors make to cost growth. For example, both the Young Task Force (Defense Science, 2003) and the GAO (Government, 2006) studies identify requirements creep as a contributor to cost growth; however, because they are qualitative studies, they do not reveal how much cost growth can be attributed to requirements creep. A quantitative study using regression analysis, on the other hand, would be able to forecast the percent increase in cost growth for each additional requirement (or for a given percent growth in requirements).

Graphical Analyses

Cost and schedule growth studies employ an assortment of methods for displaying data in graphical and tabular form. Although these methods do not provide the reader with a quantitative measure of the relationship between the factor of interest and growth, they are an effective means of visually displaying data and identifying patterns. One of the most common methods is the use of bar graphs and histograms, as shown by McCrillis (2003) in Figure 8. In this graph, McCrillis divides total cost growth into increments of ten percent, and then displays the number of systems (frequency) that falls into each increment. From this graph, the reader can gather that most systems experience

relatively little cost growth (between -10% and 20%). Interestingly, a high number of systems experience extreme cost growth (greater than 70%).

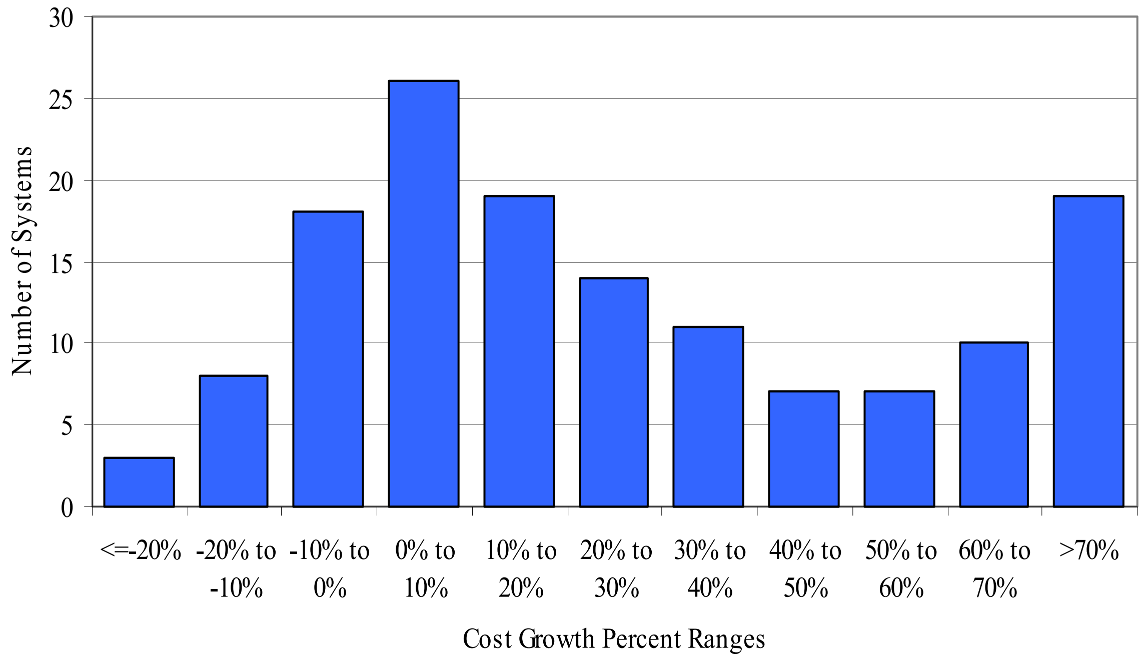


Figure 8. Total Cost Growth Distribution (McCrillis, 2003)

Presenting comparisons in tabular form is another common method for conveying the relationship between a single factor and growth. In the case of Table 2, cost growth factors are displayed by weapon system type (commodity class). Table 2 allows for quick comparisons; for example, electronics experience relatively low cost growth (CGF 1.23), where as missiles experience relatively high cost growth (CGF 1.52). Although displaying data in graphical and tabular form allows for quick identification of patterns and trends, this methodology limits the researcher's ability to interpret the data. Graphs and tables provide summaries of the data in the sample; however, they neither reveal

whether the relationships in the data are statistically significant nor do they provide the researcher with the ability to make predictions about the relationships in the population from which the data are drawn.

Table 2. Cost Growth Factor by Commodity Class (Arena et al., 2006)

Commodity	**Mean**	**Standard Deviation**	**Number of Observations**
Aircraft	1.35	0.24	9
Cruise missiles	1.64	0.40	4
Electronic aircraft	1.52	0.47	5
Electronics	1.23	0.33	12
Helicopters	1.76	0.21	3
Launch vehicles	2.30	N/A	1
Missiles	1.52	0.38	8
Other	1.40	N/A	1
Satellites	1.55	0.57	2
Vehicles	1.67	N/A	1

Regression Analyses

The preferred quantitative methodology among DoD cost and schedule growth studies is regression analysis (Foreman, 2007; Gounatidis, 2006; McNicol, 2005; Tyson et al., 1994; Tyson et al., 1992a; Wolf, 1990). DoD cost and schedule growth studies employ three types of regression analyses: simple linear regression, multiple regression, and logistic regression. Simple linear regression quantitatively describes a linear relationship (Figure 9) between two variables: a single predictor variable (for example, size of program) and the response variable (cost growth). It does so with a straight-line

equation that expresses the response variable (*y*) as a function of the predictor variable (*x*) (Schwab, 2005).

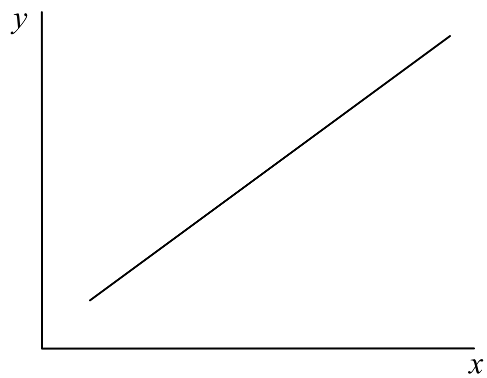


Figure 9. Linear Relationship

However, simple linear regression limits the researcher to examining the effects of one variable at a time. Because there are numerous possible predictors of cost or schedule growth, multiple regression is a more effective tool. Multiple regression captures the relationship between multiple predictor variables and a response variable. With multiple regression, one can determine the relationship between a predictor variable and response variable while controlling for the effects of other predictor variables (Schwab, 2005). For example, to examine the relationship between cost growth and acquiring service, one might create a simple linear regression model to predict cost growth based on service and find that Army programs correspond with higher cost growth. However, if the Army programs in the dataset tend to be smaller than the Navy programs, this difference could be problematic, since Dameron et al.'s (2002) study finds that size impacts cost growth with smaller programs correlating with higher cost growth. Thus, the results are unclear as to whether Army programs correspond with higher cost

growth or smaller programs correspond with higher cost growth. By using multiple regression, one can determine the relationship between service and cost growth while controlling for program size, thus resolving the dilemma faced by using simple linear regression.

Another benefit to multiple regression is that the relationship between the predictor and response variables is not limited to a linear relationship; rather, multiple regression allows for non-linear relationships (McClave et al., 2005). For example, if the relationship between cost growth and years of development increases initially and then decreases after a certain point, a quadratic model would be more appropriate (Figure 10).

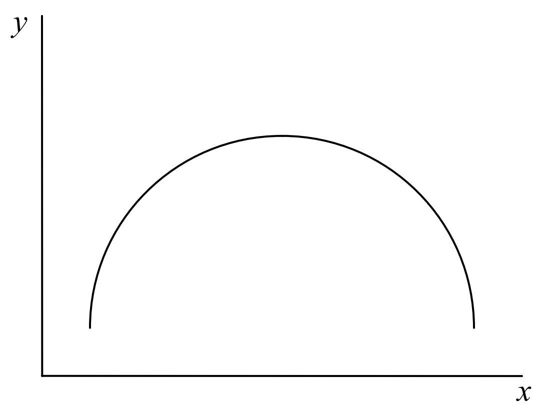


Figure 10. Quadratic Relationship

In addition to simple and multiple regression, a series of AFIT theses, beginning with Sipple (2002), also includes logistic regression in order to create models in which the response variable is binary (that is, the response has only two possible values). In the case of these AFIT theses, the analyses use a two-stage process consisting of logistic and multiple regression. First, logistic regression models are built from the entire dataset in order to predict whether or not a weapon system program is likely to experience cost or schedule growth (response value either “yes” or “no”). Then, multiple regression models

are built from the portion of the dataset that experienced cost or schedule growth in order to predict how much growth will occur (Cross, 2006; Monaco, 2005; Genest, 2004; Lucas, 2004; McDaniel, 2004; Rossetti, 2004; Bielecki, 2003; Moore, 2003; Sipple, 2002). If the models were to simply use multiple regression for the entire dataset, a large portion of the data points would have values of zero. This would result in a dilution in the predicted amount of growth as well as result in violation of some assumptions required for regression analyses, such as normality and constant variance for the residuals (the difference between the predicted and actual value) (Bielecki and White, 2005). See Chapters III and IV for a more detailed discussion of logistic regression and residual analyses.

Chapter Summary

This chapter has reviewed previous cost and schedule growth studies examining all defense programs, as well as those that focus exclusively on space systems. The literature review reveals that space system cost and schedule growth studies have been sparse and primarily qualitative, while quantitative studies analyzing cost and schedule growth for all defense programs have been numerous. By reviewing the literature, this chapter has laid the foundation for answering four of the investigative questions:

1. Which systems should be considered "space systems"?
2. What are the current methods for calculating cost and schedule growth?
3. What characteristics of the program or acquisition environment are good predictors of cost and schedule growth?
4. What are the current methodologies for predicting cost and schedule growth?

With respect to Investigative Question 1, the literature reveals several definitions for "space system." The most restrictive definitions consider "space systems" to be only those systems operating in the space environment, such as satellites. Broader definitions can include launch vehicles, space system ground equipment, and even strategic missiles. Limiting "space systems" to include only those operating in the space environment has the advantage of ensuring that one is comparing similar systems ("apples to apples"). However, by using the restrictive definition, researchers do not capture the entire system necessary for executing space missions. If the focus is on the DoD space acquisition community, the restrictive definition does not capture all of the systems this community acquires since the DoD space acquisition community is responsible for acquiring not only space-based, but also land-based assets including strategic missiles.

When exploring Investigative Question 2, cost and schedule growth studies provide two methods for calculating growth, as a percentage or as a growth factor. For cost growth, the major differences in the calculations are not in the formulas, but rather in the definition of actual and estimated costs. These differences include: how far along in development a program needs to be, which variances to include, and how to adjust for quantity.

Investigative Question 3 provides valuable insight into predictors of cost and schedule growth. Interestingly, for cost growth, the qualitative studies and the quantitative studies differ on the factors they considered and thus differ on which factors they find contribute most to cost growth. The most likely cause of this disconnect is that quantitative studies often limit their predictor variables to those available in the SAR, and

many of the factors considered in qualitative studies are unlikely to be available for the large number of programs considered by quantitative studies.

With respect to Investigative Question 4, the literature demonstrates a range of qualitative and quantitative methodologies for assessing the predictors, with each method having strengths and limitations. Qualitative methods, such as case studies, provide the advantage of a depth of understanding into the programs being examined, but the small sample size limits the ability to generalize the results to other systems. Quantitative methods, such as regression analysis, provide the advantage of statistical rigor and enable the researcher to numerically assess how much a predictor contributes to cost or schedule growth. However, quantitative methods may be limited by available data, and thus unable to account for all factors contributing to space system cost or schedule growth.

The literature reviewed herein contributes to this study by providing a greater understanding of how past researchers have defined space systems, calculated cost and schedule growth, identified predictors, and assessed those predictors. This study builds upon this literature over the course of the next several chapters. Chapter III presents this study's definition of "space system," method for calculating growth, and methodology for predicting space system cost and schedule growth. Chapter IV incorporates the predictors identified by the literature to quantitatively assess which predictors are best for predicting space system cost and schedule growth.

III. Methodology and Data

Chapter Overview

This study defines "space systems" using the broadest definition: including not only satellites and spacecraft, but also launch vehicles, strategic missiles, and space-related ground equipment. This study uses two separate sets of data: Department of Defense (DoD) data and National Aeronautics and Space Administration (NASA) data. The DoD dataset includes satellites, launch vehicles, strategic missiles, and space-related ground equipment; the NASA dataset only includes spacecraft and satellites. This chapter begins with the discussion of the methodology used by this study, and concludes with a discussion of each of the datasets. Each dataset discussion details the data source, the response variables and how they are calculated, the potential predictor variables, and the diagnostics used to validate the models.

Methodology

Figure 11 presents the methodology used in this study. The methodology begins with collection of the data, proceeds to a preliminary and inferential analysis of the data, and concludes with interpreting the results.

Data Collection

The literature review aids the data collection process by identifying potential predictor variables, as well as sources of data for previous studies. In the case of this study, two separate datasets are compiled – one for DoD space systems and one for NASA space systems. These datasets are kept separate due to the differences in the types of space systems included and the available data for the predictor variables.

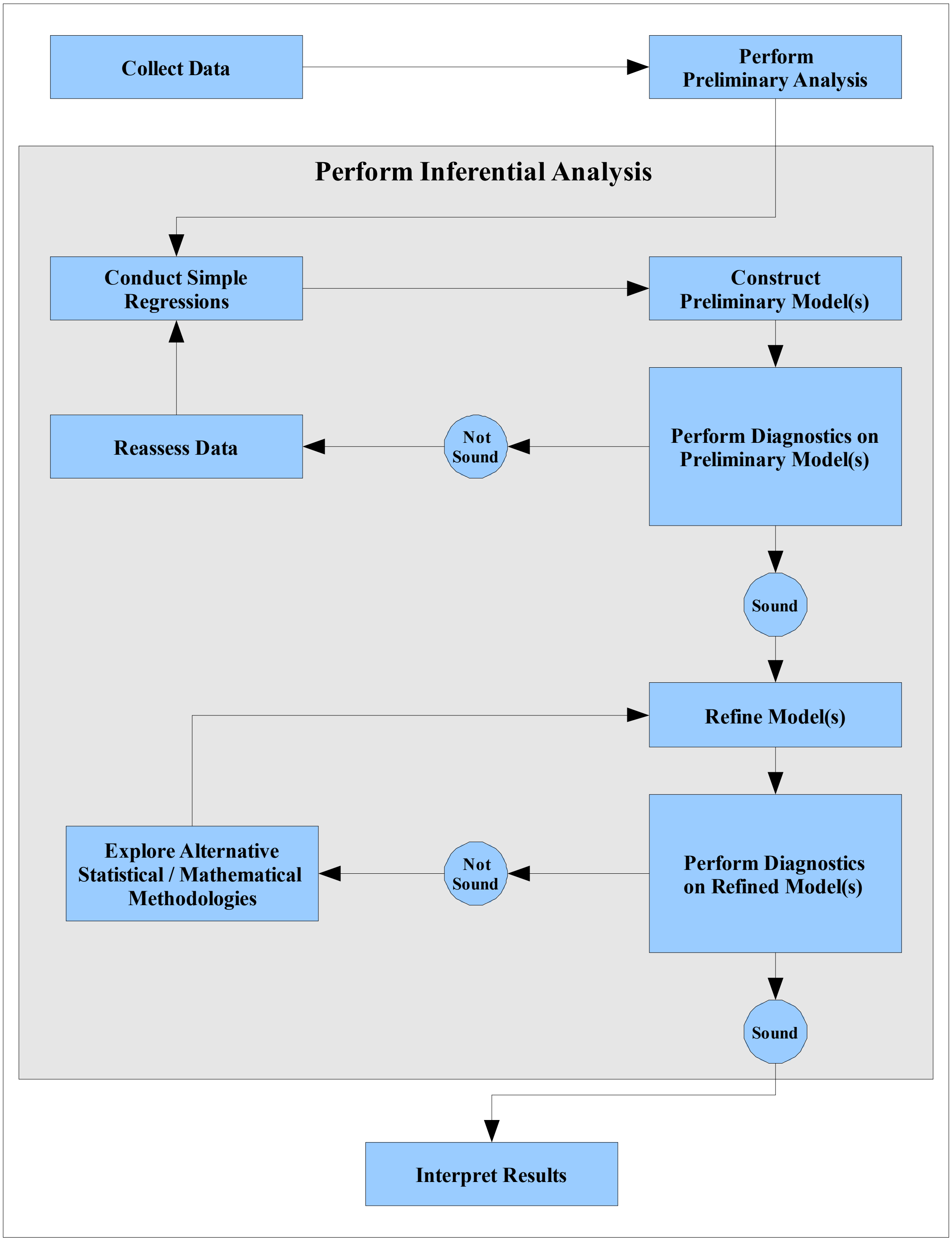


Figure 11. Methodology Flow Chart

The primary source of data for DoD space systems is the Selected Acquisition Report (SAR) (Selected, 2003; “Selected,” 2007; “DAMIR,” 2007). As discussed in Chapter II, the SAR includes cost, schedule, and programmatic information for Major Defense Acquisition Programs. The DoD dataset consists of data for 21 programs including satellites, launch vehicles, missiles, and ground equipment. See DoD data discussion herein for more detailed information regarding the data used in this study.

The NASA dataset combines data from two previous cost growth studies: the 1992 Institute for Defense Analyses study (Tyson et al., 1992a) and the 2004 NASA Headquarters Cost Analysis Division study (Schaffer, 2004). Additional data were added to this dataset based on publicly available online NASA sources including National Space Science Data Center (“NSSDC,” 2007), JPL Mission and Space Craft Library (“MSL,” 2007), and NASA’s Science Mission Directorate (“Science,” 2007). Personal communications with program personnel provided additional data. The NASA dataset includes cost, schedule, and descriptive data for 71 satellites and spacecraft. The availability of schedule data for 47 of these systems allows for this study to include an analysis of schedule growth in addition to cost growth. See NASA data discussion herein for more detailed information regarding the data used in this study.

After compiling the data into their respective datasets, the data go through a rigorous “data scrub.” This data scrub includes analyses on individual variables to ensure that all of the values have been entered correctly and all calculated fields are correctly tabulated. Additionally, the data scrub identifies any unusual patterns or observations within a particular variable. For example, Figure 12 displays a histogram of the cost growth values for the DoD space systems. As can be seen, there is an outlier that has

three times the cost growth of the next highest observation. This observation is noted and may be removed later on if it unduly influences the models.

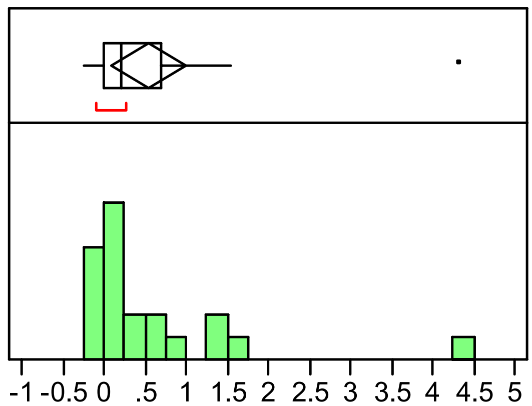


Figure 12. Histogram of DoD Cost Growth

In addition to identifying single points that are unusual, the data scrub also identifies unusual patterns, such as distributions that appear bimodal[11] rather than normal. Unusual patterns may indicate the need to create additional variables to capture these patterns. See the discussion herein on the NASA response variables, for details on creating logistic response variables to capture bimodal distributions.

Preliminary Analysis

The cost and schedule growth analysis begins with the use of graphical descriptive methods. These methods compare the cost/schedule growth response variable to a single predictor variable using bar charts to compare means. After identifying potential patterns, the Preliminary Analysis uses Student's t-tests to determine the statistical significance of these relationships. Correlation analyses are also used to

[11] Bimodal distributions have two distinct modes (that is, two relative maximum values). Such a distribution may represent two separate distributions.

identify relationships between predictor variables. See Chapter IV for the Preliminary Analysis and more information on the analytical techniques used.

Inferential Analysis

Simple Regressions. The inferential statistical analysis begins with performing simple regressions. For each response variable, each predictor variable is regressed against it individually to determine which predictors are the best indicators of cost or schedule growth. This consists of several dozen regressions for each response variable.

Preliminary Model. Those predictor variables that are significant at the 5% level represent the main drivers for that response variable and are carried forward to the preliminary model. Based on the correlation analysis from the Preliminary Analysis, if two predictors are highly correlated, then only the predictor that was more predictive (in terms of significance level) is carried forward. The preliminary model combines all non-correlated significant predictor variables into a single model.

Preliminary Model Diagnostics. In order to validate the models, the preliminary model undergoes numerous diagnostic tests. For linear regression models, this includes comparing the R^2 and adjusted R^2, using Cook's Distance to identify influential data points, testing the studentized residuals for normality using the Shapiro-Wilk Test, and testing the residuals for constant variance using the Breusch-Pagan test. For logistic models, diagnostics include assessing the R^2 (U), studying the ROC Curve, and comparing the Wald and Likelihood Ratio Parameter Estimates to identify unstable variables. If the diagnostics reveal that the model is sound, then the model proceeds to the refinement stage. If the diagnostics reveal that the model is not sound, the individual variables are revisited for adjustment. This could include removal of influential data

points, transformations (such as logarithmic) of the response or predictor variables, identification of new predictor variables, or transforming a variable from a continuous variable to a discrete variable.

Model Refinement. In order to identify the most predictive model(s), the preliminary model undergoes an iterative process of running hundreds of regressions by adding and removing the remaining predictor variables individually and in groups to determine if the addition or removal of such variables adds value to the model. Refinement also includes testing for interaction terms and higher-order terms, such as quadratics. These new models are evaluated against the preliminary model and each other by comparing the R^2 and adjusted R^2 for linear regression models and by comparing the R^2 (U) and using the Likelihood Ratio tests for logistic models.

Refined Model Diagnostics. In order to validate the refined models, these models undergo the same diagnostics as the preliminary models. If the diagnostics reveal that the model is theoretically sound, the most predictive model(s) are established as the final model(s). Otherwise, the data or methodology goes through additional adjustments. See Chapter IV for the final models.

Results

After establishing the final models, the analysis proceeds to an interpretation of the models and associated predictor variables. See Chapter V for the discussion of the results, limitations to the results, and recommendations for further study.

DoD Space Systems Dataset

The DoD dataset uses information annually reported to Congress through the SAR. The 21 space programs included in this dataset are satellites, launch vehicles,

strategic missiles, and space-related ground equipment reported in SARs between 1969 and 2006 (see Appendix A for a complete list of the space systems). The dataset includes total costs of all variance categories (with the adjustments described herein) for both development and procurement costs associated with the development phase of system acquisition (Phase B: Design Phase, see Figures 3 and 4 in Chapter I). Like most studies using SAR data, this study uses a mix of completed and on-going programs. To ensure enough cost data were available for each program, this study follows the example of McNichol (2005) by setting a minimum requirement that a program had to have reported SARs for at least three years in order to qualify for inclusion.

It is important to recognize that using SAR data has a number of drawbacks, primarily due to the nature of the reporting process. Hough (1992) notes a number of limitations from using data from the SAR including:

- Programs do not always use a consistent baseline for the cost estimates
- Not all elements of cost are included
- Certain classes of programs, such as special access programs, are not included
- Guidelines for preparing SARs change over time
- Differences exist in the interpretation of preparation guidelines
- Some programs account for risk by including reserve funds in cost estimates
- Inconsistencies exist in reporting for programs that share costs between services
- Cost changes are reported in terms of their effects rather than root causes

While recognizing these limitations, this study chooses to use SAR data because it does provide a significant amount of consistency in the type of data that is collected and the format in which that data is available.

DoD Response Variables

The DoD response variables include *Total Cost Growth* and *Per Unit Cost Growth*. Due to the inconsistency in records of schedule data, this analysis does not include an assessment of DoD space system schedule growth.

Total Cost Growth. The *Total Cost Growth* response variable compares the actual or most current estimate (CE) to the original development estimate (DE) from the initiation of Milestone B. The CE is adjusted for quantity changes by subtracting the cost growth listed in the Quantity Variance category. Both the DE and CE are adjusted for inflation by converting both into Constant Year 2007 (CY07) dollars. Cost Growth is then calculated using Equation 3, which provides Cost Growth in terms of a percentage, where a value of "zero" means there is no cost growth, a negative value means that the actual cost (CE) is less than the planned costs (DE), and a positive value means that the actual cost (CE) is greater than the planned cost (DE).

$$\text{Cost Growth} = \frac{(\text{CE-DE})}{\text{DE}} \tag{3}$$

Since military cost growth studies and current defense acquisition policies are inconsistent as to whether or not strategic missiles are treated as space systems, this study is interested in analyzing the defense data both with and without inclusion of these systems. Figure 13 shows the histogram for the 21 programs in the DoD dataset. The histogram reveals the degree to which the data for the response variable represents a normal distribution. Although normality is not required, tests on preliminary models from this dataset reveal that the lack of normality for this distribution leads to numerous problems with the residual diagnostics, and thus this lack of normality prevents adequate

modeling of this variable. Using the Shapiro-Wilk Test to assess the normality of the distribution yields a p-value of <0.0001. Since this is well below the 0.05 level of significance, the test rejects the null hypothesis that the data are from a normal distribution. As can be seen visually from Figure 13, a single point (Titan IV) clearly prevents this distribution from being a normal distribution.

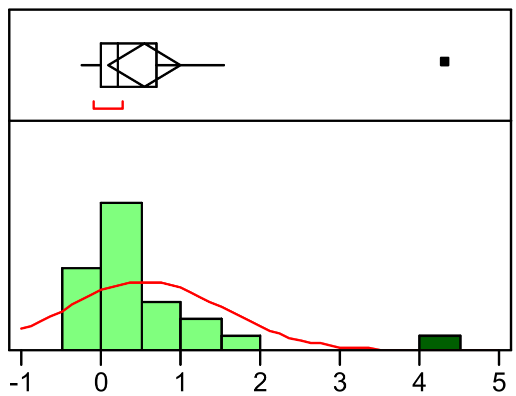


Figure 13. Histogram of DoD *Total Cost Growth*

Omitting this single observation (Figure 14), improves the distribution's Shapiro-Wilk Test p-value to 0.0092; however, this value is still too low, thus rejecting that the data are from a normal distribution. Even with the removal of Titan IV, preliminary models continue to have numerous problems with residual diagnostics. Thus, the data are unable to be sufficiently analyzed in the current form.

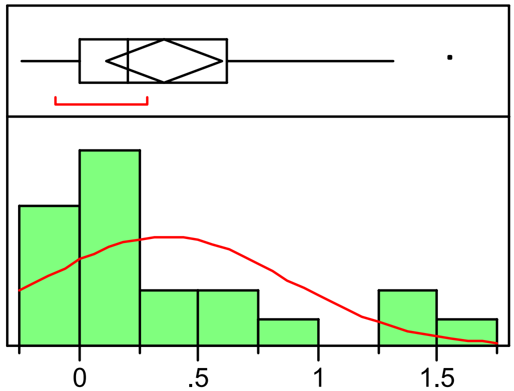


Figure 14. Histogram of DoD *Total Cost Growth*,
Titan IV omitted

Since analysis of space systems excluding strategic missiles is also of interest, the analysis tests the data excluding these observations to see if normality is still an issue. Figure 15, displays the histogram for *Total Cost Growth* after removing Titan IV and the five strategic missile observations. This distribution's Shapiro-Wilk Test p-value is 0.0542, thus failing to reject that the data are from a normal distribution. Although borderline, this is a significant improvement, and this dataset of 15 points is carried forward into the analysis for *Total Cost Growth*. Thus, in the case of *Total Cost Growth*, the analysis focuses only on space systems excluding strategic missiles.

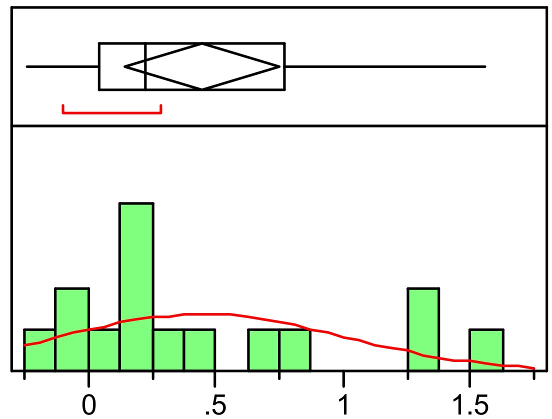


Figure 15. Histogram of DoD *Total Cost Growth*,
Excluding strategic missiles and Titan IV

Per Unit Cost Growth. Similar to the *Total Cost Growth* response variable, the *Per Unit Cost Growth* response variable compares the actual or most current estimate (CE) to the original development estimate (DE), adjusted for inflation into CY07 dollars. The *Per Unit Cost Growth* response variable accounts for changes in quantity by adjusting both the DE and the CE into a per unit cost, using Equation 4:

$$\text{Per Unit Cost Growth} = \frac{[(\text{CE/\# of unit for CE})-(\text{DE/\# of units for DE})]}{\text{DE/\# of units for DE}} \tag{4}$$

Figure 16 displays the *Per Unit Cost Growth* response variable using all 21 observations (includes strategic missiles). Visually, the graph appears normal, and it has a Shapiro-Wilk Test p-value of 0.4811, well above the 0.05 level of significance, thus failing to reject that the data are normally distributed.

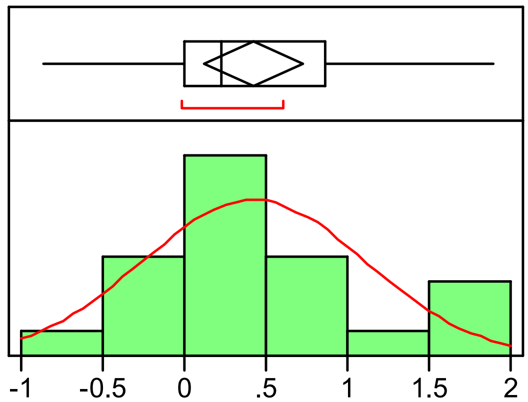


Figure 16. Histogram of DoD *Per Unit Cost Growth*

Recognizing the utility of a model that excludes strategic missiles, the study also considers the data without the inclusion of these systems. Figure 17 displays the *Per Unit Cost Growth* response variable excluding the strategic missile observations. Visually, this graph also appears normal, and it has a Shapiro-Wilk Test p-value of 0.7052, thus failing to reject that the data are normally distributed. Thus, the *Per Unit Cost Growth* response variable is carried forward for analysis using both versions (with and without strategic missiles).

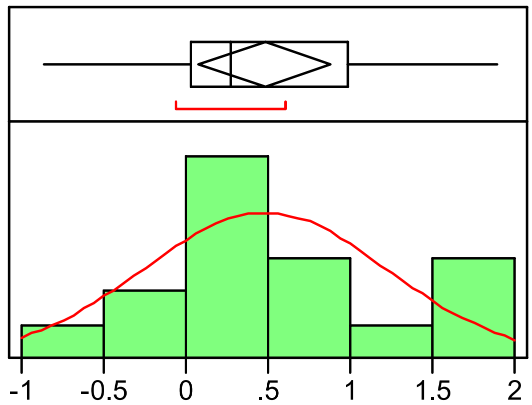


Figure 17. Histogram of DoD *Per Unit Cost Growth*
Excluding strategic missiles

DoD Predictor Variables

The study assesses the predictor variables to determine which characteristics are indicators of cost growth. Some of these, such as *Commodity Type*, have been used in past quantitative cost growth studies, others such as *Program Manager Tenure* are inspired by the qualitative space studies, and others such as *Mission Type* are new additions.

Commodity Type. This predictor captures the commodity classification of the particular program. The attribute is represented in the dataset by three separate binary variables: *Satellite*, *Launch Vehicle/Missile*, and *Ground Equipment*. In each case, the variable is assigned a value of "1" if the system belongs to that category and a value of "0" otherwise.

Mission Area. This attribute captures the type of mission for the program (note that a program may belong to more than one mission area). As with *Commodity Type*, *Mission Area* is measured by four separate binary variables: *Communications*,

Navigation, *Earth Observation* (such as visual or infrared scanning), and *Space Support* (those systems that perform a significant portion of their mission on land, such as launch vehicles, strategic missiles, and ground equipment). In each case, the variable is assigned a value of "1" if the system belongs to that category and a value of "0" otherwise.

Program Size. This attribute is a continuous variable measured in terms of actual system cost in CY07 dollars. As discussed in the literature review, some studies have found that smaller programs are associated with higher cost growth.

Development Duration. This is a continuous variable measuring the number of years between the first development estimate and the last development estimate included in the study. As discussed in the literature review, studies have found that those programs with longer development periods (or programs further along in their development) are associated with higher cost growth. Due to the inconsistency in records of schedule data, it was not possible to include other schedule variables.

Program Managers. Qualitative DoD space systems studies identified high rotation of Program Managers as a contributor to space system cost growth. Thus, two Program Manager variables have been included: *# of PMs* and *PM Tenure*. *# of PMs* is a discrete variable measuring the number of Program Managers during the system's development phase, while *PM Tenure* is a continuous variable measuring the average tenure of a Program Manager, calculated by dividing the *Development Duration* by the *# of PMs.*

Baselines. Adjusting the baseline is an indication of major program restructuring. Thus, two baseline variables have been included to attempt to capture major programmatic changes. The first, *# of Baselines* is a discrete variable measuring the

number of baselines for the system. The second, *Baselines/yr* is a continuous variable measuring the number of baselines adjusted for length of the development, calculated by dividing the *# of Baselines* by the *Development Duration*.

Contract Type. This attribute captures the type of contracts that were used in the development of the program. It is measured by two separate binary variables: *Cost Plus Award Fee (CPAF)* and *Firm Fixed Price (FFP).* In each case, the variable is assigned a value of "1" if the system belongs to that category and a value of "0" otherwise. Note that there are other contract types available, but these two are the most widely used for the programs in the DoD dataset. Many programs use multiple contract types for various portions of development. Thus, it is feasible for a program to have both a CPAF and a FFP contract or to have neither.

Lead Service: Air Force. This is a binary variable with a value of "1" if the system was developed by the Air Force and a value of "0" otherwise.

Cost Breach. This is a binary variable with a value of "1" if the system experienced a cost breach [cost exceeded 10% of objective cost reported in the Acquisition Program Baseline (APB) (Axtell and Irby, 2007)] during development and a value of "0" otherwise.

Schedule Breach. This is a binary variable with a value of "1" if the system experienced a schedule breach [schedule exceeded 6 months from objective schedule reported in the APB (Axtell and Irby, 2007)] during development and a value of "0" otherwise.

Prime Contractor. This attribute is measured by four separate binary variables: *Lockheed Martin*, *Boeing*, *Northrop Grumman*, and *Other Contractor.* In each case, the

variable is assigned a value of "1" if the system was developed by that contractor (or one of that contractor's predecessors) and a value of "0" otherwise. Note that in some cases, a system may have multiple prime contractors.

NASA Space Systems Dataset

The NASA dataset includes data compiled from the 1992 Institute for Defense Analyses study (Tyson et al., 1992a); the 2004 NASA Headquarters Cost Analysis Division study (Schaffer, 2004); publicly available online NASA sources including National Space Science Data Center ("NSSDC," 2007), JPL Mission and Space Craft Library ("MSL," 2007), and NASA's Science Mission Directorate ("Science," 2007); as well as data collected through personal communications with program personnel. The NASA dataset includes cost, schedule, and descriptive data for 71 satellites and spacecraft from 1964 to 2004. The cost data includes total development costs through the launch of the spacecraft. Unlike the DoD dataset which includes both completed and on-going programs, all 71 NASA programs have completed development and been launched. See Appendix B for a complete list of the NASA programs used in this study. Since initial launch estimates and actual launch dates were available for 47 of the programs in the NASA dataset, the response variables include both cost and schedule growth.

NASA Response Variables

NASA Cost Growth. Similar to the DoD cost growth response variables, the NASA *Cost Growth* response variable compares actual development costs to the initial estimate in terms of a percentage, using Equation 5. The estimate and actual costs are adjusted for inflation by converting both into Constant Year 2007 (CY07) dollars. Because NASA programs tend to be formulated around the development of a single

system, with each spacecraft considered a separate program, quantity adjustments are not required.

$$\text{Cost Growth} = \frac{(\text{Actual-Estimate})}{\text{Estimate}} \tag{5}$$

The histogram (Figure 18) of NASA *Cost Growth* reveals that a number of data points fall at the high end of the distribution, which may cause the data to not represent a normal distribution. Testing for normality using the Shapiro-Wilk Test, provides a p-value of <0.0001. Since p-values less than 0.05 lead to the rejection of the null hypothesis that the data is from a normal distribution, it is suspected that the values at the high end of the NASA *Cost Growth* data represent a separate distribution.

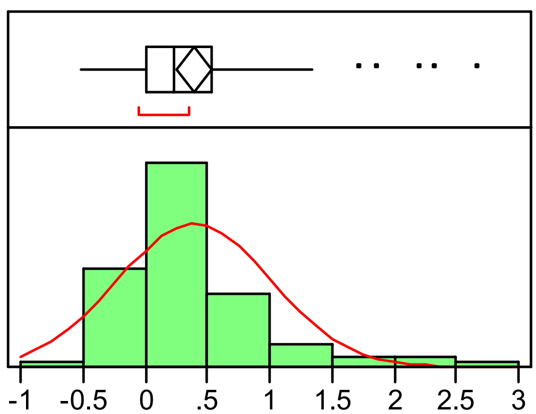


Figure 18. Histogram of *Cost Growth* response variable for NASA systems

Thus, the NASA *Cost Growth* distribution is divided into two distributions: low *Cost Growth* (consisting of 62 observations) and high *Cost Growth* (consisting of 9 observations). After removing the high cost growth programs, the histogram for low

Cost Growth (Figure 19) reveals a normal distribution with a Shapiro-Wilk Test p-value of 0.7143. Since this is greater than 0.05, the Shapiro-Wilk Test fails to reject the null hypothesis that the data is from the normal distribution.

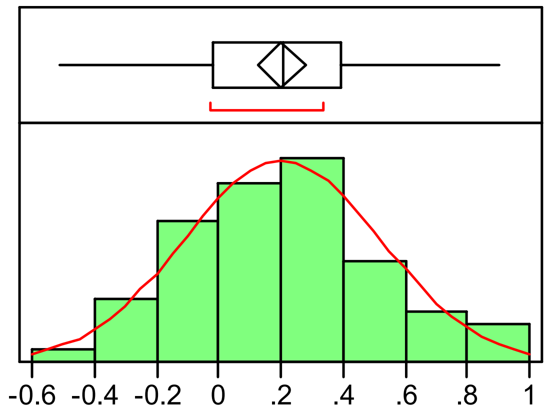


Figure 19. Histogram of low *Cost Growth* response variable for NASA systems

Due to the small sample size ($n = 9$), it is unclear from a visual examination of the histogram for high *Cost Growth* (Figure 20) whether these values represent a normal distribution. Fortunately, the Shapiro-Wilk Test was designed for small sample sizes; Shapiro and Wilk (1965) originally designed the test for $2 \leq n \leq 50$, and the test has been shown to be robust for samples $n \leq 2000$ ("JMP®", 2005; Arthur and Seber, 1984). Testing the distribution of the high *Cost Growth* programs for normality results in a Shapiro-Wilk p-value of 0.3468; since this is greater than 0.05, the Shapiro-Wilk Test fails to reject the null hypothesis that the data is from the normal distribution. Given that the full NASA *Cost Growth* distribution did not pass the test for normality, but the division of it provides two distributions that do pass the test for normality, it is concluded

that the NASA *Cost Growth* response represents a bimodal distribution. Thus, in order to model cost growth for NASA space systems, it is best to separately model low *Cost Growth* and high *Cost Growth*.

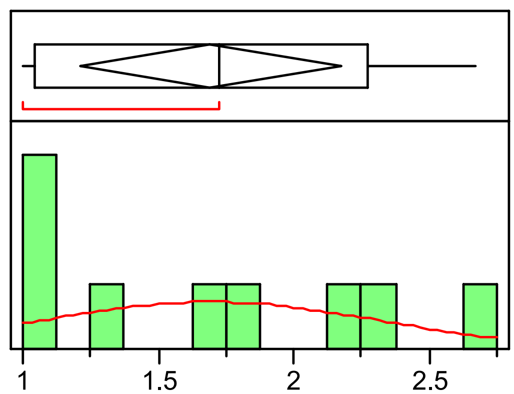


Figure 20. Histogram of high *Cost Growth* response variable for NASA systems

Adapting from the technique implemented by Sipple (2002), this study employs logistic regression to determine whether or not a program is likely to experience high cost growth using the binary variable *High Cost Growth?* with a value "1" for high cost growth programs and a value of "0" for low cost growth programs. Logistic regression uses maximum likelihood to estimate the parameters that best model the data, creating a likelihood function that expresses the probability (as a value between 0 and 1) that the independent variables predict the dependent variable. For our purposes, a probability greater than or equal to 0.5 (50%) predicts a program will experience high cost growth, and a probability of less than 0.5 predicts the program will *not* experience high cost growth. See Sipple (2002) for more information on the logistic response function.

Thus, the first response variable, *High Cost Growth?,* is a binary variable measuring the likelihood that a program will experience high cost growth. The second response variable, *Cost Growth*, is a continuous variable that measures the percentage of cost growth that a program is likely to incur. Because the NASA *Cost Growth* response represents a bimodal distribution, the analysis models this variable twice, once for each distribution, thus providing a High Cost Growth Linear Regression Model and a Low Cost Growth Linear Regression Model.

Schedule Growth. The *Schedule Growth* response variable compares the planned launch date to the actual launch date for 47 NASA space systems. Both dates are measured in the number of months they occur from program initiation. As with *Cost Growth*, *Schedule Growth* is calculated as a percentage using Equation 6.

$$\text{Schedule Growth} = \frac{(\text{Actual Launch Schedule - Planned Launch Schedule})}{\text{Planned Launch Schedule}} \tag{6}$$

Similar to *Cost Growth*, the histogram of *Schedule Growth* (Figure 21) does not appear to represent the normal distribution. The Shapiro-Wilk Test rejects the null hypothesis that the data are from the normal distribution with a p-value of <0.0001.

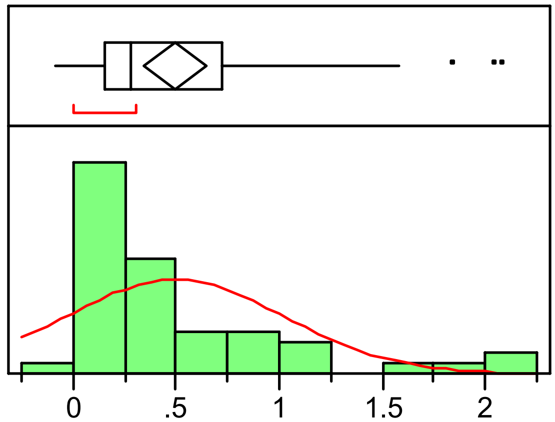


Figure 21. Histogram of *Schedule Growth* response variable for NASA systems

Using the same methodology as with *Cost Growth*, the *Schedule Growth* distribution is divided into two, to see if it represents a bimodal distribution. Figures 22 and 23 provide the histograms for low *Schedule Growth* (36 observations) and high *Schedule Growth* (11 observations), respectively. Using the Shapiro-Wilk Test, both distributions fail to reject the null hypothesis that the distributions represent a normal distribution, with a p-value of 0.0842 for low *Schedule Growth* and a p-value of 0.0504 for high *Schedule Growth*.

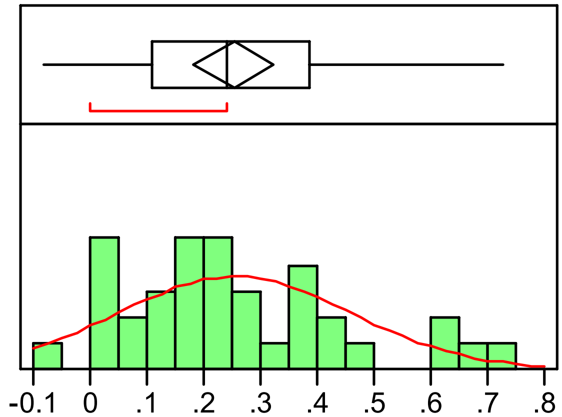


Figure 22. Histogram of low *Schedule Growth* response variable for NASA systems

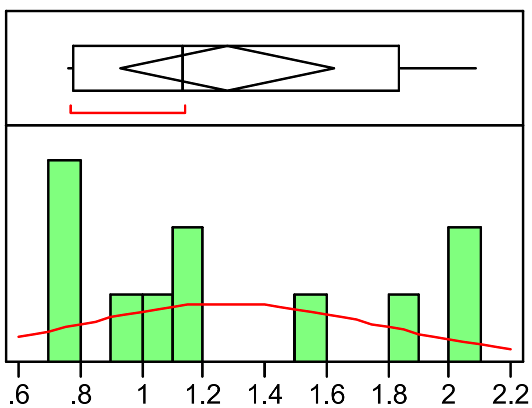


Figure 23. Histogram of high *Schedule Growth* response variable for NASA systems

Thus, this study models NASA *Schedule Growth* in the same manner as NASA *Cost Growth*, by first using a binary response variable, *High Schedule Growth?*, to determine whether or not the program is likely to experience high schedule growth.

Then, the study uses a continuous response variable, *Schedule Growth*, to separately model high and low *Schedule Growth* programs.

NASA Predictor Variables

The study assesses a number of predictor variables to determine which characteristics are indicators of cost or schedule growth. The predictors include programs size, program start, schedule (for cost growth response), cost growth (for schedule growth response), mission area, international participation, developer, life span, and mass.

Program Size. There are two program size variables: *Initial Program Size* and *Final Program Size*. *Initial Program Size* is a continuous variable measured in terms of the original estimate of the system cost in CY07 dollars. *Final Program Size* is a continuous variable measured in terms of actual system cost in CY07 dollars. As discussed in the literature review, some studies have found that smaller programs are associated with higher cost growth.

Program Start. This is a continuous variable measured as the number of years from 1964 (this year was chosen as the baseline since it represents the earliest start date in the dataset).

Schedule Characteristics. There are three schedule predictor variables: *Estimated Time to Launch*, *Actual Time to Launch*, and *Schedule Growth*. *Estimated Time to Launch* is a continuous variable measuring the initial planned launch date in number of months from program initiation. *Actual Time to Launch* is a continuous variable measuring the actual launch date in number of months from program initiation. *Schedule Growth* is a continuous variable measuring the percent growth between the estimated and

actual launch schedule: (actual date – planned date)/planned date. The schedule predictor variables are used with the cost growth response variables only.

Cost Growth. *% Cost Growth* is a continuous variable measuring the percent growth between the estimated and actual cost (See Equation 6). The *% Cost Growth* predictor variable is used with the schedule growth response variables only.

Mission Area. This attribute captures the type of mission for the program as catalogued in the National Space Science Data Center database ("NSSDC," 2007). Mission area is measured by ten binary variables: *Space Physics*, *Engineering*, *Earth Science*, *Planetary Science*, *Astronomy*, *Solar Physics*, *Human Crew*, *Communications*, *Life Science*, and *Microgravity.* In each case, the variable is assigned a value of "1" if the system belongs to that category and a value of "0" otherwise. Note that a program may have more than one mission area.

International Participation. This is a binary variable capturing whether or not countries other than the U.S. participated in the scientific, technical, or design elements of the spacecraft. The variable is assigned a value of "1" if the system included international participation and a value of "0" otherwise.

Developer. This attribute measures the primary organization responsible for designing and manufacturing the spacecraft. It is measured by nine binary variables: *NASA*, *Jet Propulsion Laboratory*, *Johns Hopkins University*, *Lockheed Martin*, *Boeing*, *Northrop Grumman*, *DoD*,[12] *International Developer*, and *Other Developer*. In each

[12] Two DoD programs, DSCS-2 and SCATHA are included in the NASA dataset. A number of NASA databases have included the cost, schedule, and technical data of these programs due to their similarity to other NASA programs.

case, the variable is assigned a value of “1” if the system was developed by that organization and a value of “0” otherwise.

Life Span. There are two life span predictor variables: *Design Life* and *Actual Life*. *Design Life* is a continuous variable measuring the intended design life of the spacecraft in months. *Actual Life* is a continuous variable measuring the actual life span, or current estimate of the life span for programs still in operation, in months.

Mass. There are two mass predictor variables: *Total Mass* and *Dry Mass*. *Total Mass* is a continuous variable measuring the total mass of the spacecraft in kilograms, including consumable propellants, at the time of launch. *Dry Mass* is a continuous variable measuring the mass of the spacecraft in kilograms, excluding consumable propellants, at the time of launch.

Chapter Summary

This chapter discussed the methodology and data used by this study to predict cost and schedule growth for space systems. The methodology includes collecting and reviewing the data, performing preliminary analyses, performing inferential analyses, and then interpreting the results.

The DoD dataset includes cost and programmatic data for 21 space-related programs from 1969 through 2006, including satellites, launch vehicles, strategic missiles, and ground equipment. From this dataset, two response variables have been identified: *Total Cost Growth* and *Per Unit Cost Growth*. Additionally, the study identified a number of programmatic characteristics as potential predictors of cost growth. Chapter IV includes the Preliminary Analysis and Inferential Analysis for both of these responses.

The NASA dataset includes cost, schedule, and descriptive data for 71 satellites and spacecraft from 1964 to 2004. From this dataset, two response variables have been identified: *Cost Growth* and *Schedule Growth*. Due to the bimodal distribution of these two variables, the analysis begins by using logistic regression to determine whether or not the program is likely to experience high growth and then employs separate linear regressions for high and low growth to predict the quantity of growth. As with the DoD dataset, the NASA dataset discussion includes identifying programmatic characteristics that are potential predictors of cost and schedule growth. Chapter IV includes the Preliminary Analysis and Inferential Analysis for both of these responses.

IV. Analysis

Chapter Overview

As discussed in the Methodology section of Chapter III, the analysis consists of two segments: the Preliminary Analysis and the Inferential Analysis. This chapter begins by detailing the Preliminary Analysis for the Department of Defense (DoD) data set, followed by the Preliminary Analysis for the National Aeronautics and Space Administration (NASA) dataset. The Preliminary Analysis compares response values for individual predictor variables, as well as identifies potential relationships between predictor variables. The chapter then details the Inferential Analysis, beginning with the DoD dataset and concluding with the NASA dataset. The Inferential Analysis includes logistic and linear regression models useful for predicting cost and schedule growth.

Preliminary Analysis

The Preliminary Analysis includes graphical analyses, Student's t-tests (t-test), and correlation analyses for select predictor variables. The graphical analyses include bar graphs of mean (average) growth values by predictor variable in order to identify potential predictors. Because examining solely the mean values amongst groups can be misleading, the Preliminary Analysis includes performing t-tests to determine if the differences in the means are significant. The Preliminary Analysis also includes correlation analyses between predictor variables to allow for the identification of multicollinearity[13] issues. The discussion herein details only those tests with significant results.

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[13] Multicollinearity occurs when two or more predictor variables are intercorreltated. When two highly correlated predictors are used in a regression model, they create linear redundancy in the model and diminish the accuracy of the regression coefficients (Gujarat, 1995:320-322).

Preliminary Analysis: DoD

Total Cost Growth. The study performed preliminary analyses for the *Program Manager Tenure*, *Contractor*, *Commodity Type*, *Mission Area*, and *Program Size* predictor variables, using all 21 programs in the DoD dataset.

Figure 24 displays average *Total Cost Growth* by prime contractor: Lockheed Martin, Boeing, Northrop Grumman, and other contractors. From the graph, it appears that programs developed by Lockheed Martin experience higher cost growth than other prime contractors. Using a one-tailed t-test to test the alternate hypothesis of unequal means results in a p-value of 0.0925, therefore programs developed by Lockheed Martin do experience higher cost growth than the other three contractor categories at the significance level of 10%, but these results are not significant at the 5% level.

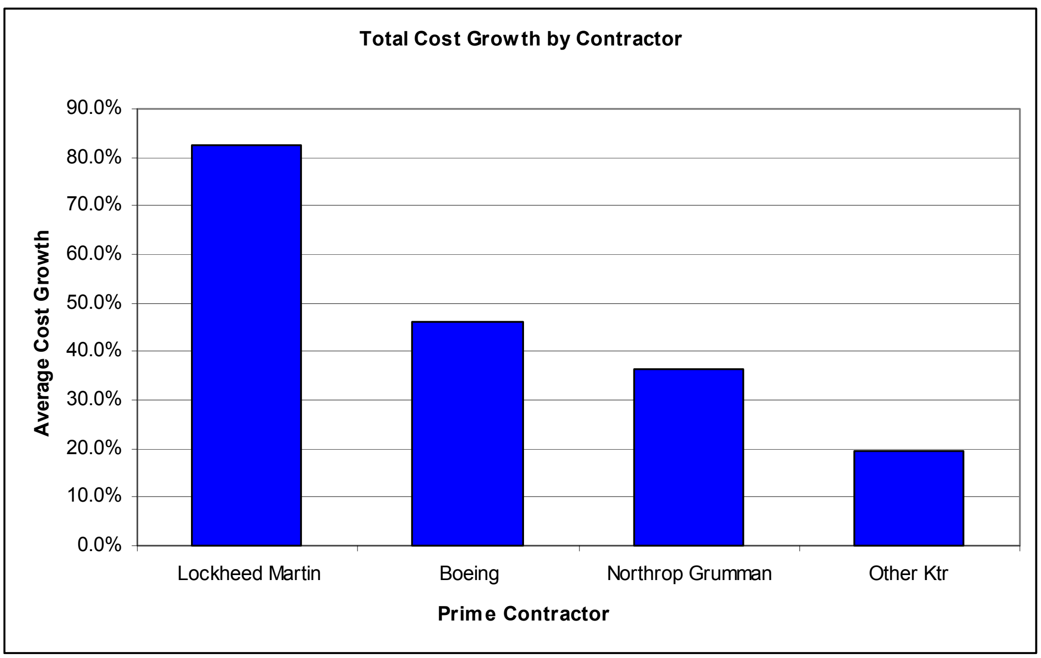


Figure 24. DoD Total Cost Growth by Prime Contractor

Figure 25 displays *Total Cost Growth* by *Commodity Type*. From viewing the graph, it appears that ground equipment has the lowest cost growth and launch vehicles/missiles have the highest cost growth. A one-tailed t-test for ground equipment results in a p-value of 0.0262, well below a 5% significance level; however, the one-tailed t-test for launch vehicles/missiles fails to reject the null hypothesis of equal means with a p-value of 0.2063. Thus, ground equipment systems have statistically significant lower cost growth than other systems.

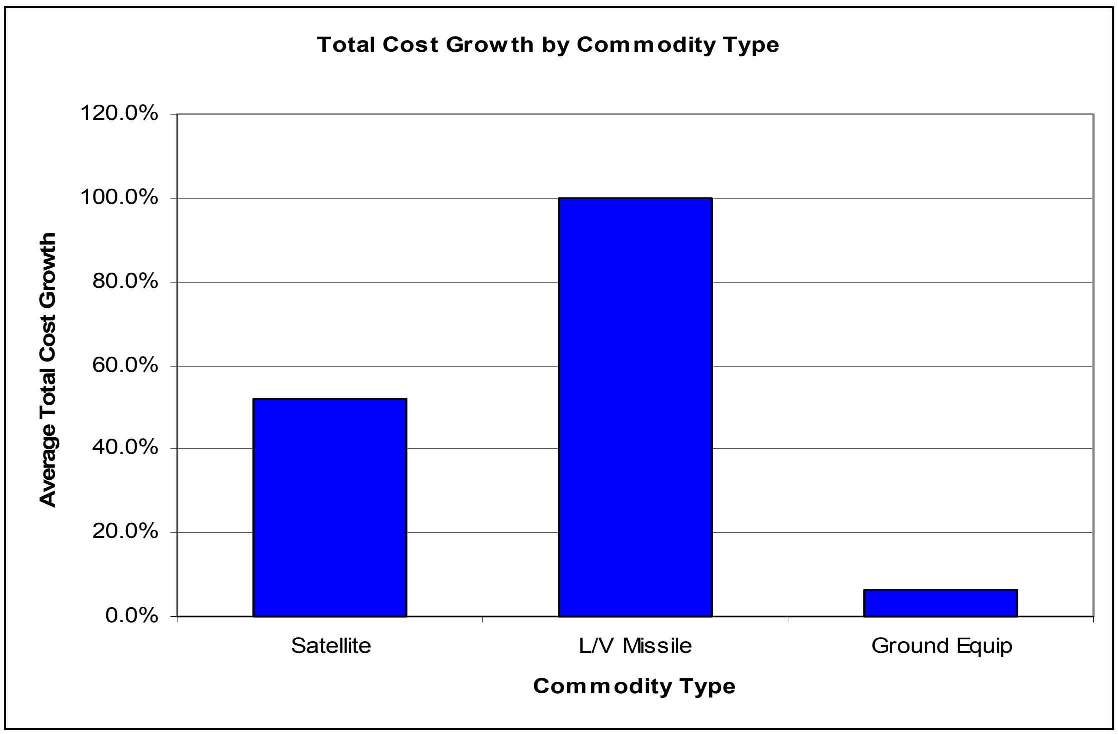


Figure 25. DoD Total Cost Growth by Commodity Type

Figure 26 displays *Total Cost Growth* by *Mission Area*. Visual examination leads to the alternate hypothesis that communications missions have lower cost growth than other missions. A one-tailed t-test for communications missions results in a p-value of 0.0447, thus rejecting the null hypothesis of equal means. Thus, systems with

communications missions have statistically significant lower cost growth than other systems.

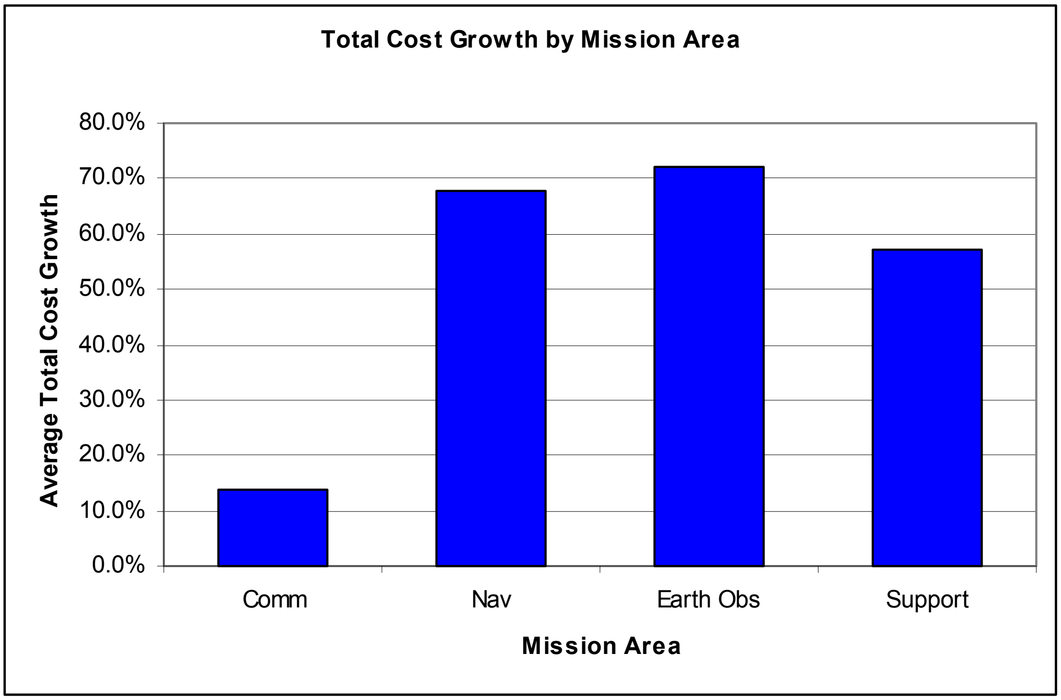


Figure 26. DoD Total Cost Growth by Mission Area

Per Unit Cost Growth. As with *Total Cost Growth*, the preliminary analyses assessed *Per Unit Cost Growth* using all 21 programs in the DoD dataset. Figure 27 displays *Per Unit Cost Growth* by *Commodity Type*. Similar to *Total Cost Growth,* it appears that ground equipment has lower per unit cost growth. A one-tailed t-test for ground equipment rejects the null hypothesis with a p-value of 0.0074, well below a 5% or even 1% significance level. Thus, ground equipment systems have statistically significant lower per unit cost growth than other systems.

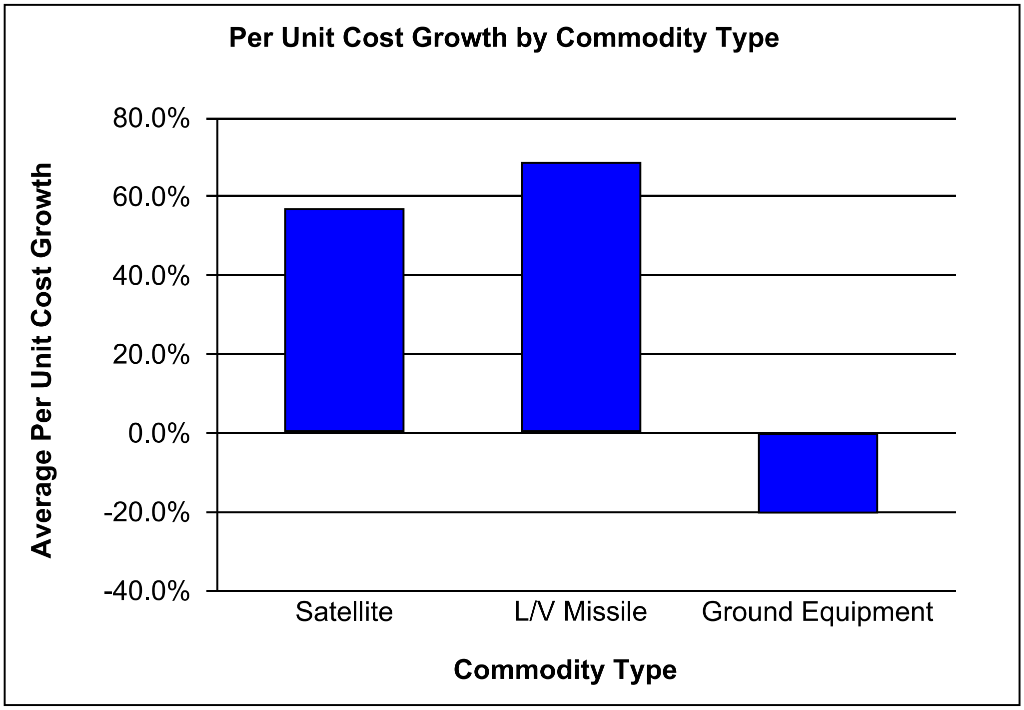


Figure 27. DoD Per Unit Cost Growth by Commodity Type

Figure 28 displays *Per Unit Cost Growth* by *Mission Area*. Visual examination leads to the alternate hypothesis that earth observation missions have higher per unit cost growth than other missions. However, a one-tailed t-test for earth observation missions results in a p-value of 0.1089, just barely failing to reject the null hypothesis at the 10% level.

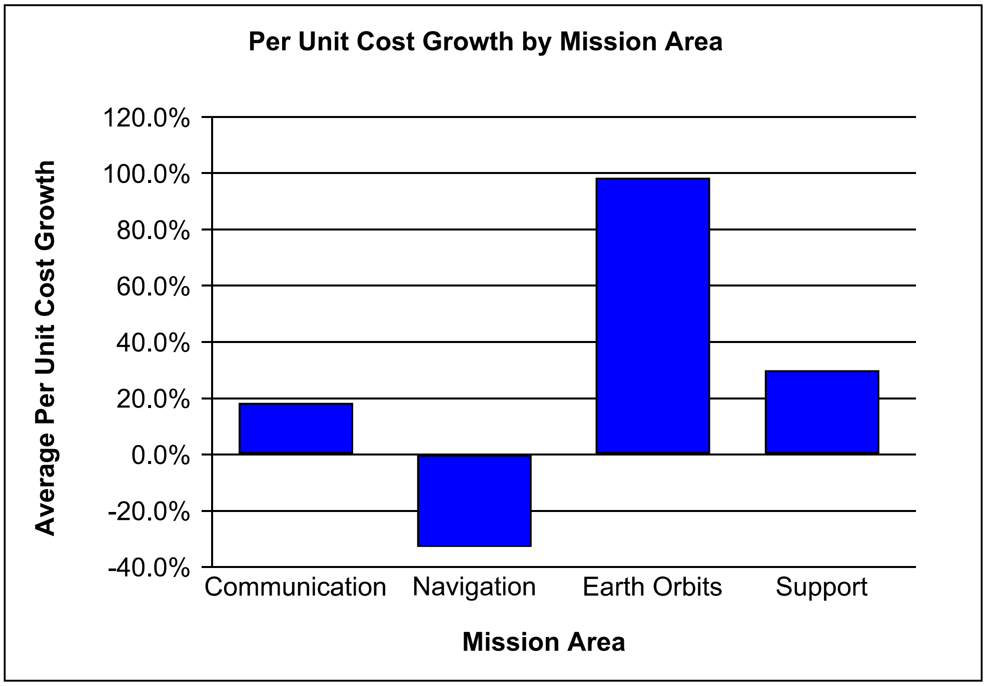


Figure 28. DoD Per Unit Cost Growth by Mission Area

Predictor Correlations. The Preliminary Analysis also includes performing correlation analysis on the predictor variables in the DoD dataset in order to identify any variables that may exhibit similar behaviors, and thus lead to multicollinearity issues. If two predictors are highly correlated, using both in a model can create linear redundancy and diminish the accuracy of the regression coefficients (Gujarat, 1995:320-322). Franzblau (1958) identifies correlations values between 0.60 and 0.80 (or between -0.60 and -0.80) as having a "marked degree of correlation" and values between 0.80 and 1.00 (or between -0.80 and -1.00) as having a "high correlation." Table 3 provides correlation values for those predictor variables that have correlations greater than 0.6 or less than -0.6.

Table 3. Correlations between DoD Predictor Variables

	# of PMs	Development Duration	Cost Breach	# of Baselines	Launch Vehicle/ Missile	Satellite	Navigation	Space Support
# of PMs	1.00	0.92	0.73	0.86			0.65	
Development Duration		1.00	0.71	0.82			0.63	
Cost Breach			1.00	0.66				
# of Baselines				1.00			0.73	
Launch Vehicle/Missile					1.00	-0.60		
Satellite						1.00		-1.00
Navigation							1.00	
Space Support								1.00

In the case of the *# of Program Managers*, *Development Duration*, *Cost Breach*, and *# of Baselines*, time is most likely the underlying factor that ties these variables together; that is, programs that have had longer development periods would be expected to have higher values for each of these. During the regression analysis, if two highly correlated variables were to both appear significant, then including both would cause linear redundancy in the analysis. In this case, the variable that is most predictive (in terms of significance level) is kept in the model.

Preliminary Analysis: NASA

The study includes preliminary analyses for cost and schedule growth with the *Mission Area*, *Developer*, *Program Size*, and spacecraft *Mass* variables. The cost analyses used all 71 programs in which cost data were available, and the schedule analyses used all 47 programs in which schedule data were available. The discussion herein details those tests with significant results.

NASA Cost Growth. Figure 29 displays average *Cost Growth* by *Developer*. Note that while the average cost growth for *DoD* programs is far greater than for the other developer categories, this dataset only includes two *DoD* programs. A one-tailed t-test for the alternate hypothesis that *DoD* programs have higher cost growth fails to reject the null hypothesis with a p-value of 0.1591. However, a one-tailed t-test for the alternate hypothesis that programs developed by *Johns Hopkins* have lower cost growth rejects the null hypothesis with a p-value of 0.0419, and a similar test for *NASA* developed programs is significant at the 10% level with a p-value of 0.0893. Thus, systems developed by Johns Hopkins have statistically significant lower cost growth than other systems at the 5% level, and systems developed by NASA have statistically significant lower cost growth than other systems at the 10% level.

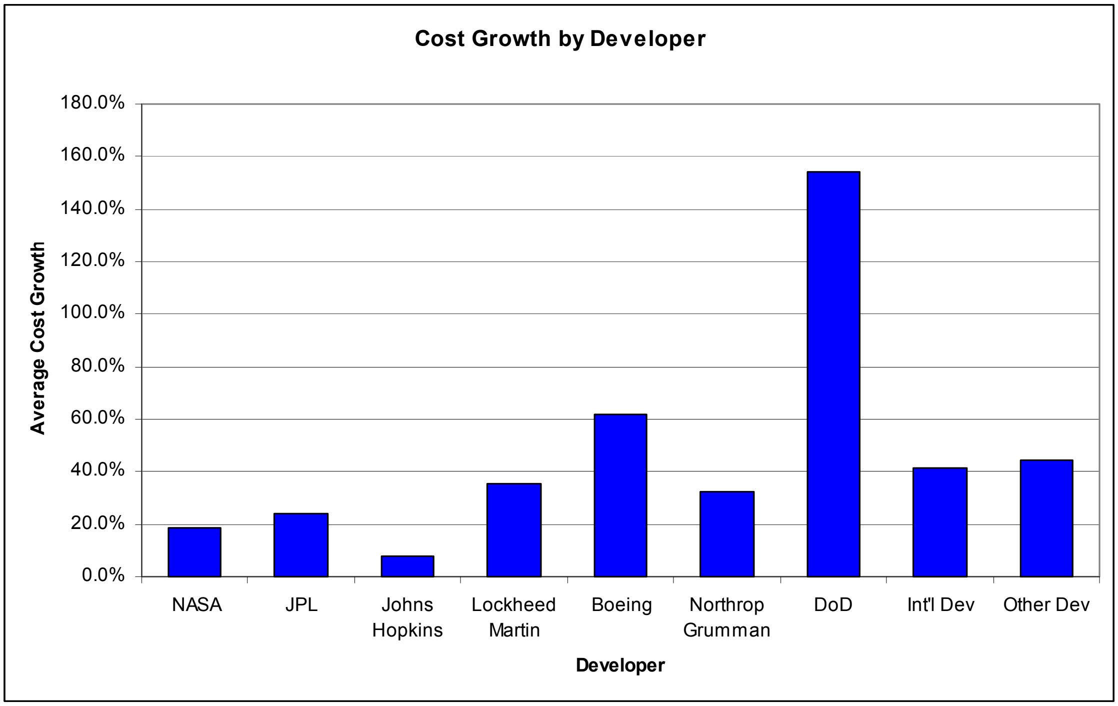


Figure 29. NASA Cost Growth by Developer

Schedule Growth. Figure 30 displays average *Schedule Growth* by *Developer*. From this figure, it appears that *Johns Hopkins*, *Boeing*, and *Other Developer* are associated with low schedule growth and *NASA*, *Jet Propulsion Laboratory*, *Northrop Grumman*, and *International Developer* are associated with high schedule growth. One-tailed t-tests on these variables find that these relationships are significant for: *Johns Hopkins* with a p-value of <0.0001, *Boeing* with a p-value of 0.0112, *Northrop Grumman* with a p-value of 0.0826, and *Other Developer* with a p-value of 0.0242. Thus, systems developed by Johns Hopkins, Boeing, and Other Developers have statistically significant lower cost growth than other systems, and systems developed by Northrop Grumman have statistically significant higher cost growth than other systems.

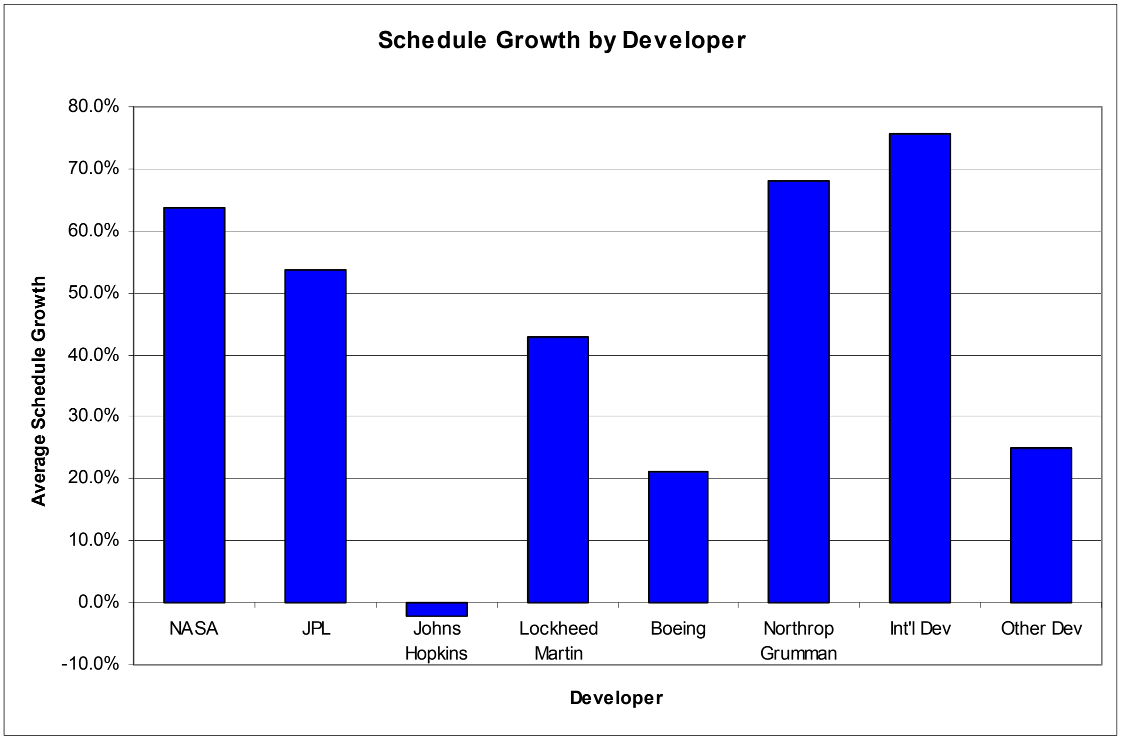


Figure 30. NASA Schedule Growth by Developer

Predictor Correlations. Correlation analysis was preformed on the predictor variables in the NASA dataset in order to identify any variables that may exhibit similar behaviors. Table 4 provides only those correlations that are greater than 0.6 or less than -0.6. As with the DoD predictor correlations, if two highly correlated variables both appear significant during the regression analysis, then the variable that is most predictive (in terms of significance level) is kept in the model.

Table 4. Correlations between NASA Predictor Variables

	Human Crew	Life Science	Microgravity	Int'l Participation	Int'l Developer	Total Mass	Dry Mass
Human Crew	1.00	0.86	0.70				
Life Science		1.00	0.81				
Microgravity			1.00				
Int'l Participation				1.00	0.64		
Int'l Developer					1.00		
Total Mass						1.00	0.99
Dry Mass							1.00

Inferential Analysis: DoD

Total Cost Growth

As discussed in Chapter III, due to the non-normality of the distribution when including all of the systems in the DoD dataset, the *Total Cost Growth* analysis excludes strategic missiles and Titan IV. The remaining 15 systems include all satellites, other launch vehicles, and all space-related ground equipment. Equation 7 provides the final model for predicting *Total Cost Growth* using the methodology outlined in Chapter III:

$$CG_T = 0.715 - 0.577*(\mathit{Communications}) \tag{7}$$

where CG_T is the dependent variable and is the predicted *Total Cost Growth* as a percentage of the system's original estimate, and *Communications* is a binary variable with a value of "1" for those systems with a communications mission and a value of "0" otherwise. The negative coefficient on the *Communications* variable indicates that those systems with a communications mission experience lower cost growth than compared to other missions. To assess the ability of the parameter in the model to explain the variation in the response, the analysis examines both the R^2 and the adjusted R^2.[14] The R^2 for this model is 0.29 and the adjusted R^2 is 0.24. The relatively low values of the R^2 and the adjusted R^2 indicate that much of the variation in *Total Cost Growth* is explained by factors outside of the model. Appendix C provides the complete output provided by the JMP Software (JMP®, 2005) for this regression.

The analysis applies numerous diagnostics to the model in order to test its robustness. The first diagnostic is the Cook's Distance test for influential data points. With this test, values over 0.5 indicate possible influential data points (Neter et al., 1996:381). The Cook's Distance for the *Total Cost Growth* model had all points below 0.3, thus indicating that there are no influential data points present. The second diagnostic tests the studentized residuals for normality using the Shapiro-Wilk Test. With this test, a p-value below 0.05 rejects the null hypothesis that the residuals are normally distributed. Since the optimal model will have normally distributed studentized

[14] R^2 and adjusted R^2 range from "0" to "1," where a value of "1" indicates that the parameters explain 100% of the variation of the response, and a value of "0" indicates that the parameters provide no explanation. Since an increase in the number of variables will result in an increase in the R^2, the adjusted R^2 is also referenced because it accounts for the number of predictor variables used in the model. Thus, while a saturated model (one with unnecessary predictor variables) may have a high R^2, the saturated model will not have as high of an adjusted R^2. Ideally, the model builder would want both R^2 and adjusted R^2 to be close to "1," as well as close to each other.

residuals, this requires Shapiro-Wilk p-values over 0.05. The *Total Cost Growth* model had a Shapiro-Wilk p-value of 0.4631; thus failing to reject the null hypothesis. The final diagnostic applied to the *Total Cost Growth* model tests the residuals for constant variance using the Breusch-Pagan Test. With this test, a p-value below 0.05 rejects the null hypothesis that the residuals have constant variance. Thus, similar to the Shapiro-Wilk Test, because the optimal model will have constant variance of its residuals, this requires Breusch-Pagan p-values over 0.05. The Breusch-Pagan p-value for the *Total Cost Growth* model was 0.1110.

Per Unit Cost Growth

The models for predicting *Per Unit Cost Growth* include the entire DoD dataset, as well as excluding strategic missiles in order to provide a model similar to the one provided for *Total Cost Growth*. Using the methodology outline in Chapter III, the entire DoD dataset yielded two separate models for predicting *Per Unit Cost Growth*. Equations 8 and 9 provide these models:

$$CG_{U1} = 0.869 - 0.941*(\textit{Ground Equip}) - 0.661*(\textit{FFP}) \tag{8}$$

where CG_{U1} is the dependent variable and is the predicted *Per Unit Cost Growth* as a percentage of the system's original estimate for unit cost, *Ground Equip* is a binary variable with a value of "1" for ground equipment systems and a value of "0" otherwise, and *FFP* is a binary variable with a value of "1" for systems developed using a Firm Fixed Price contract and a value of "0" otherwise. The negative coefficients on both the *Ground Equipment* and *Firm Fixed Price* variables indicate that both of these factors are associated with lower *Per Unit Cost Growth*. The R^2 for this model is 0.50 and the

adjusted R^2 is 0.44. Appendix D provides the complete output provided by the JMP Software (JMP®, 2005) for this regression.

The model's diagnostics are satisfactory with all points having a Cook's Distance below 0.15, the studentized residuals Shapiro-Wilk p-value of 0.7392, and the residuals Breusch-Pagan p-value of 0.0581. Because the Breusch-Pagan p-value is very close to the rejection point of being below 0.05, the analysis examines the plot of the residuals versus the predicted values (Figure 31) to identify the extent to which the residuals have non-constant variance. From Figure 31, it appears that a single point to the far left may be driving this low Breusch-Pagan p-value. Removing this observation increases the Breusch-Pagan p-value to 0.0721. Appendix E provides the complete output provided by the JMP Software (JMP®, 2005) for this regression with the single observation removed.

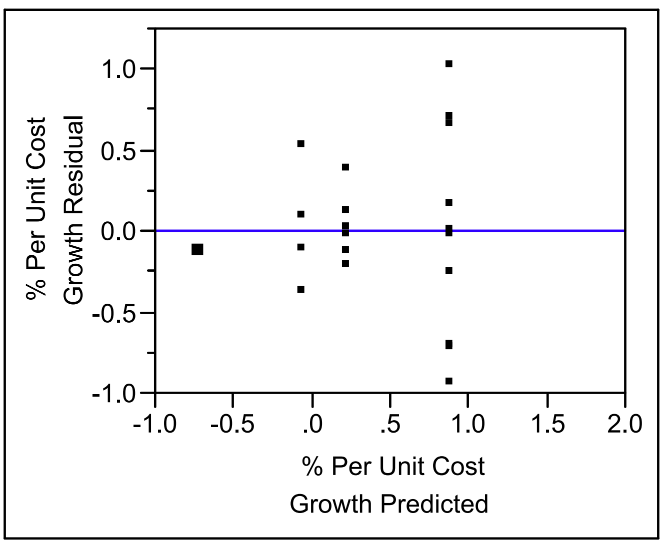


Figure 31. Residuals versus Predicted Plot for
DoD *Per Unit Cost Growth* Model 1

The second model for predicting *Per Unit Cost Growth* is:

$$CG_{U2} = 2.069 - 1.178*(\textit{Ground Equip}) - 0.664*(\textit{PM Tenure}) \tag{9}$$

where CG_{U2} is the dependent variable and is the predicted *Per Unit Cost Growth* as a percentage of the system's original estimate for unit cost, *Ground Equip* is a binary variable with a value of "1" for ground equipment systems and a value of "0" otherwise, and *PM Tenure* is a continuous variable representing the average Program Manager Tenure. The negative coefficients on both the *Ground Equipment* and *PM Tenure* variables indicate that both of these factors are associated with lower *Per Unit Cost Growth*. The R^2 for this model is 0.47 and the adjusted R^2 is 0.41. Appendix F provides the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are all satisfactory with all points having a Cook's Distance below 0.15, the studentized residuals having a Shapiro-Wilk p-value of 0.3160, and the residuals having a Breusch-Pagan p-value of 0.7838.

The last model for *Per Unit Cost Growth* removes the 5 strategic missile observations from the DoD dataset, to provide a model comparable to the one for *Total Cost Growth*. Equation 10 provides this model:

$$CG_{U3} = 0.945 - 1.153*(\textit{Ground Equip}) - 0.666*(\textit{FFP}) \tag{10}$$

where CG_{U3} is the dependent variable and is the predicted *Per Unit Cost Growth* as a percentage of the system's original estimate for unit cost, *Ground Equip* is a binary variable with a value of "1" for ground equipment systems and a value of "0" otherwise, and *FFP* is a binary variable with a value of "1" for systems developed using a Firm Fixed Price contract and a value of "0" otherwise. Note that this model includes the same

factors as Equation 8, which was for the entire DoD dataset. As with Equation 8, Equation 10 also has negative coefficients for both *Ground Equipment* and *Firm Fixed Price*, indicating that both of these factors are associated with lower *Per Unit Cost Growth*. The R^2 for this model is 0.56 and the adjusted R^2 is 0.49. Appendix G provides the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are also satisfactory with all points having a Cook's Distance below 0.2, the studentized residuals having a Shapiro-Wilk p-value of 0.8562, and the residuals having a Breusch-Pagan p-value of 0.0697.

Inferential Analysis: NASA

Cost Growth

As discussed in Chapter III, due to the bimodal nature of the distribution, modeling NASA *Cost Growth* consists of a two stage process. The first stage includes a logistic regression model to determine whether a program is likely to experience high cost growth. The second stage includes separate linear regression models for both high and low cost growth to determine the likely percentage of cost growth. Note that the low cost growth model also includes zero and negative cost growth.

Logistic Regression Models. The analysis results in two logistic models for predicting the likelihood of a program to experience high cost growth; Equations 11 and 13 provide these models: [15]

$$L_{HCG1} \quad = \quad \frac{e^{\,2.140\,-\,0.058*(\textit{Initial Program Size})\,+\,0.001*(\textit{Total Mass})}}{1+e^{\,2.140\,-\,0.058*(\textit{Initial Program Size})\,+\,0.001*(\textit{Total Mass})}} \qquad (11)$$

[15] Note that JMP® uses the logistic response function: $\frac{e^{-(\beta0 + \beta1X1 \ \ \beta2X2 + \beta3X3)}}{1 + e^{-(\beta0 + \beta1X1 \ \ \beta2X2 + \beta3X3)}}$ ("JMP®", 2005).
For ease of use and interpretation, the negative sign has been multiplied through the parameter estimates it the equations provided in the text. Thus, the parameter estimates in the JMP® regression outputs in the Appendices have the opposite sign as those listed within this text.

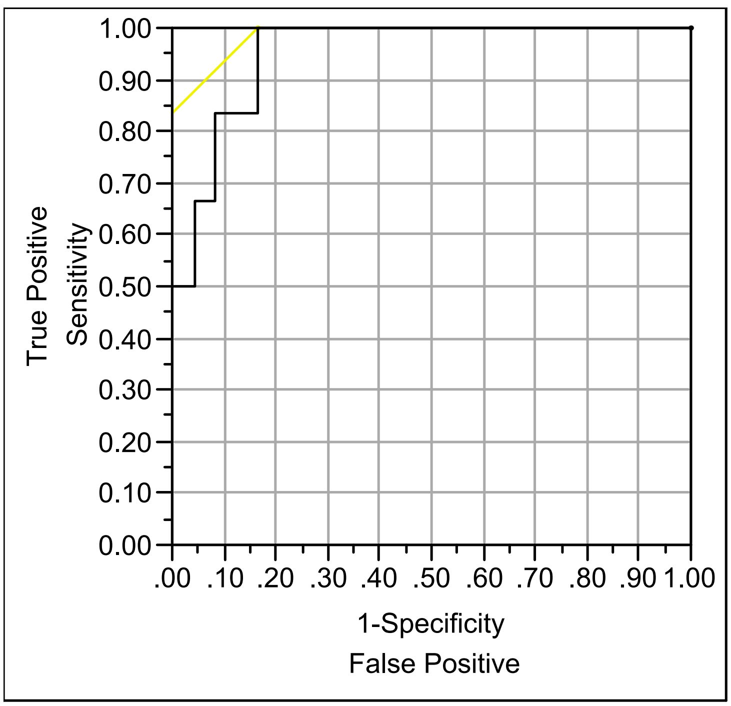
where L_{HCG} is the dependent variable and is a likelihood function that expresses the probability that a program will experience high cost growth, *Initial Program Size* is a continuous variable that measures the original estimated cost of the program in CY07 dollars, and *Total Mass* is a continuous variable that measures the mass of the spacecraft (including consumable propellants) in kilograms. For our purposes, a L_{HCG} probability greater than or equal to 0.5 (50%) predicts a program will experience high cost growth, and a probability of less than 0.5 predicts the program will not experience high cost growth. Based on the coefficients, larger *Initial Program Sizes* decreases the likelihood of experiencing high cost growth; whereas more massive spacecraft increases the likelihood of experiencing high cost growth. To assess the utility of the model, the R^2 (U) is examined. The R^2 (U) is a ratio of likelihoods (Equation 12) measuring the proportion of the total uncertainty attributed to the fitted model.

$$R^2\,(U) = \frac{\text{-Loglikelihood for Difference between Reduced and Full Model}}{\text{-Loglikelihood for Reduced Model}} \qquad (12)$$

This ratio of likelihoods compares the uncertainty from fitting the model to the uncertainty from background effects to determine whether the independent variables have an effect on the response variable ("JMP®", 2005). R^2 (U) ranges between 0 and 1, with higher values indicating a more predictive model. R^2 (U) values equal to or greater than 0.4 are desirable (White, 2007). The NASA *High Cost Growth?* model provided in Equation 11 has an R^2 (U) of 0.57. See Appendix H for the complete logistic regression output provided by the JMP Software (JMP®, 2005).

Although the diagnostics used for linear regression analysis are not available for logistic regression, the Receiver Operating Characteristic (ROC) curve can be used to

assess the model's accuracy. The ROC curve distinguishes between false-positives and true-positives, or in other words, how often the model predicts a value of "1" when the actual value is "0" compared to predicting a value of "1" when the actual value is "1." A ROC curve that runs along the 45 degree diagonal of the graph would have an area under the curve of 0.50, and would have no predictive capability. A ROC curve consisting of a vertical line from the point (0, 0) to (0, 1) and then a horizontal line from (0, 1) to (1, 1) would be perfectly predictive and have an area of 1.0. The logistic model in Equation 11 has a ROC curve area of 0.95, indicating an estimated accuracy of 95%. See Figure 32 for the ROC curve of L_{HCG1}.



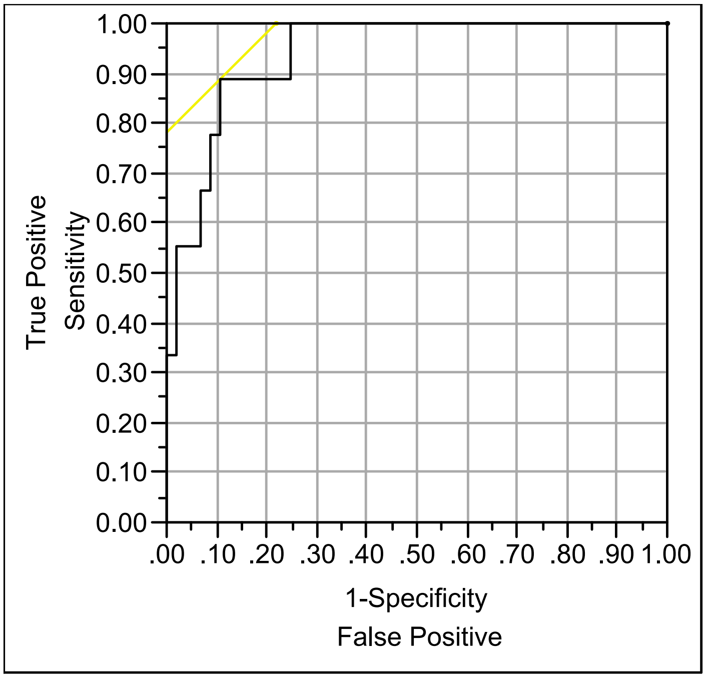
Using High Cost Growth?='1' to be the positive level
Area Under Curve = 0.95139

Figure 32. L_{HCG1} Receiver Operating Curve

Equation 13 provides the second model for predicting *High Cost Growth?*:

$$L_{HCG2} = \frac{e^{0.741 - 0.038*(\mathit{Initial\ Program\ Size}) + 0.001*(\mathit{Dry\ Mass}) + 38.705*(\mathit{Microgravity})}}{1 + e^{0.741 - 0.038*(\mathit{Initial\ Program\ Size}) + 0.001*(\mathit{Dry\ Mass}) + 38.705*(\mathit{Microgravity})}} \quad (13)$$

where L_{HCG} is the dependent variable and is a likelihood function that expresses the probability that a program will experience high cost growth, *Initial Program Size* is a continuous variable that measures the original estimated cost of the program in CY07 dollars, *Dry Mass* is a continuous variable that measures the mass of the spacecraft (excluding consumable propellants) in kilograms, and *Microgravity* is a binary variable with a value of "1" for those systems with a microgravity mission and a value of "0" otherwise. Based on the coefficients, larger *Initial Program Sizes* decreases the likelihood of experiencing high cost growth, more massive spacecraft increases the likelihood of experiencing high cost growth, and a microgravity mission increases the likelihood of experiencing high cost growth. The R^2 (U) associated with this model is 0.50, and the ROC curve area (Figure 33) is 0.94. See Appendix I for the complete logistic regression output provided by the JMP Software (JMP®, 2005).



Using High Cost Growth?='1' to be the positive level
Area Under Curve = 0.93957

Figure 33. L_{HCG2} Receiver Operating Curve

Linear Regression Models. The analysis developed separate linear regression models for high and low cost growth programs. These models are designed to be used in conjunction with the logistic regression models provided in Equations 11 and 13. If the logistic regression models predict that high cost growth is likely to occur, then the High Cost Growth Linear Regression Model (Equation 14) can be used to predict the likely percent cost growth. Similarly, if the logistic regression models predict that high cost growth is not likely to occur, the Low Cost Growth Linear Regression Model (Equation 15) can be used to predict the likely percent cost growth.

The High Cost Growth Linear Regression Model is:

$$CG_H = 1.232 + 1.037*(\textit{Space Physics}) \tag{14}$$

where CG_H is the dependent variable and is the predicted *Cost Growth* as a percentage of the original cost estimate, and *Space Physics* is a binary variable with a value of "1" for systems with a space physics mission and a value of "0" otherwise. The positive coefficient on *Space Physics* indicates that space physics missions are associated with higher *Cost Growth*. The R^2 for this model is 0.77 and the adjusted R^2 is 0.74. Appendix J provides the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are all satisfactory with all points having a Cook's Distance below 0.4, the studentized residuals having a Shapiro-Wilk p-value of 0.5716, and the residuals having a Breusch-Pagan p-value of 0.9189.

The Low Cost Growth Linear Regression Model is:

$$CG_L = 0.509 - 0.014*(\textit{Program Start}) \tag{15}$$

where CG_L is the dependent variable and is the predicted *Cost Growth* as a percentage of the original cost estimate, and *Program Start* is a continuous variable measured as the number of years from 1964. The negative coefficient on *Program Start* signifies that more recent programs are associated with lower cost growth. The R^2 for this model is 0.18 and the adjusted R^2 is 0.16. These low R^2 values indicate that most of the variation for cost growth for systems that experience low cost growth is due to factors not explained by the model. See Appendix K for the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are all satisfactory with all points having a Cook's Distance below 0.15, the studentized residuals having a Shapiro-Wilk p-value of 0.2607, and the residuals having a Breusch-Pagan p-value of 0.0841.

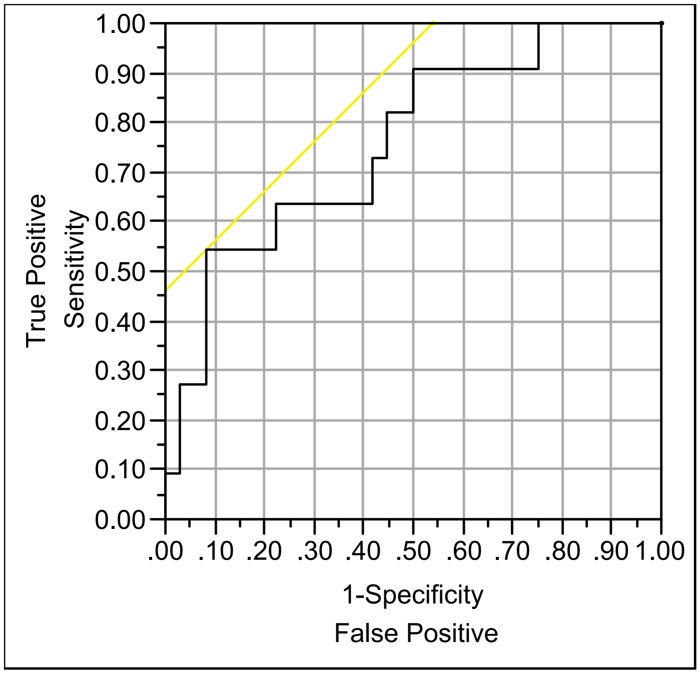
Schedule Growth

As with NASA *Cost Growth*, modeling NASA *Schedule Growth* also consists of a two stage approach: first using logistic regression to predict the likelihood of experiencing high schedule growth, then using linear regression to predict the quantity of schedule growth.

Logistic Regression Model. The logistic model for High Schedule Growth is given in Equation 16:

$$L_{HSG} = \frac{e^{-2.186 + 0.001*(\textit{Final Program Size})}}{1 + e^{-2.186 + 0.001*(\textit{Final Program Size})}} \tag{16}$$

where L_{HSG} is the dependent variable and is a likelihood function that expresses the probability that a program will experience high schedule growth, and *Final Program Size* is a continuous variable that measures the final cost of the program in CY07 dollars. The R^2 (U) associated with this model is 0.15, and the ROC curve area (Figure 34) is 0.76. The relatively low R^2 (U) and ROC curve areas indicate that this model is not as predictive as the cost growth logistic models. See Appendix L for the complete output provided by the JMP Software (JMP®, 2005) for this regression



Using High Schedule Growth?='1' to be the positive level
Area Under Curve = 0.76010

Figure 34. L_{HSG} Receiver Operating Curve

Linear Regression Models. The analysis developed separate linear regression models for high and low schedule growth programs. As with the cost growth models, these models are designed to be used in conjunction with the logistic regression model provided in Equations 16. If the *High Schedule Growth?* model predicts that high schedule growth is likely to occur, then the High Schedule Growth Linear Regression Model (Equation 17) can be used to predict the likely percent of schedule growth. If the *High Schedule Growth?* model predicts that high schedule growth is not likely to occur, then the Low Schedule Growth Linear Regression Model (Equation 18) can be used to predict the likely percent of schedule growth.

The High Schedule Growth Linear Regression Model is:

$$SG_H = 0.899 + 1.188 *(JPL) + 0.587 *(Int'l\ Develop) \tag{17}$$

where SG_H is the dependent variable and is the predicted *Schedule Growth* as a percentage of the original schedule in months from program initiation, *JPL* is a binary variable with a value of "1" for systems developed by the Jet Propulsion Laboratory and a value of "0" otherwise, and *Int'l Develop* is a binary variable with a value of "1" for systems developed by organizations belonging to countries other than the United States and a value of "0" otherwise. The positive coefficients on both *JPL* and *Int'l Develop* indicate that both of these variables are associated with higher *Schedule Growth*. The R^2 for this model is 0.79 and the adjusted R^2 is 0.73. Appendix M provides the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are: two points have a Cook's Distance over 0.5, the studentized residuals have a Shapiro-Wilk p-value of 0.8971, and the residuals have a Breusch-Pagan p-value of 0.0666. Removal of the two influential data points that have a Cook's Distance over 0.5 results in the removal of the two points that represent the *Int'l Develop* variable (total sample size is 9 observations). Removal of these two points does not affect the intercept, nor the coefficient or significance level for the *JPL* variable. The diagnostics for the model without the two influential data points are: all points have a Cook's Distance below 0.3, the studentized residuals have a Shapiro-Wilk p-value of 0.3357, and the residuals have a Breusch-Pagan p-value of 0.4450. Appendix N provides the complete output provided by the JMP Software (JMP®, 2005) for this regression with the two influential data points removed.

The Low Schedule Growth Linear Regression Model is:

$$SG_L = 0.252 + 0.243 *(Northrop\ Grumman) - 0.274 *(Johns\ Hopkins) \tag{18}$$

where SG_L is the dependent variable and is the predicted *Schedule Growth* as a percentage of the original schedule in months from program initiation, *Northrop Grumman* is a binary variable with a value of "1" for systems developed by Northrop Grumman (or its predecessors) and a value of "0" otherwise, and *Johns Hopkins* is a binary variable with a value of "1" for systems developed by Johns Hopkins University and a value of "0" otherwise. The positive coefficient on *Northrop Grumman* indicates that this developer is associated with higher *Schedule Growth*; whereas the negative coefficient on *Johns Hopkins* indicates that this developer is associated with lower *Schedule Growth.* The R^2 for this model is 0.27 and the adjusted R^2 is 0.23. These low R^2 values indicate that most of the variation for schedule growth for systems that experience low schedule growth is due to factors not explained by the model. Appendix O provides the complete output provided by the JMP Software (JMP®, 2005) for this regression. The diagnostics for this model are: one point has a Cook's Distance over 0.5, the studentized residuals have a Shapiro-Wilk p-value of 0.8105, and the residuals have a Breusch-Pagan p-value of 0.2848. Removal of the influential data point does not impact the intercept nor the coefficient or significance level for the *Johns Hopkins* variable. The removal of the influential data point increases the coefficient for Northrop Grumman from 0.243 to 0.411 and improves the significance level for this variable. The diagnostics for the model without the influential data point are: all points have a Cook's Distance below 0.1, the studentized residuals have a Shapiro-Wilk p-value of 0.0782, and the residuals have a Breusch-Pagan p-value of 0.2678. Appendix P provides the complete output provided by the JMP Software (JMP®, 2005) for this regression with the influential data point removed.

Chapter Summary

This chapter presented the Preliminary and Inferential Analysis for cost growth of DoD systems and for cost and schedule growth of NASA systems. The Preliminary Analysis explored potential relationships between individual predictors and the responses through graphical presentation. The Preliminary Analysis also identified correlations between predictor variables. The Inferential Analysis presented linear and logistic regression models for predicting cost and schedule growth, along with the diagnostics used to assess these models. The next chapter provides further discussion on these models and the predictors they identified as significant.

V. Discussion

Chapter Overview

This chapter highlights those factors found to be predictive of cost and schedule growth. The discussion begins with the predictors of Department of Defense (DoD) space system cost growth and then turns to predictors of National Aeronautics and Space Administration (NASA) space systems cost and schedule growth. The chapter concludes with a discussion of the limitations of the study and recommendations for future research.

DoD Predictor Discussion

The models for DoD cost growth provided in Table 5 reveal that communications missions, ground equipment, firm-fixed price contracts, and increased program manager tenure are all predictive of lower cost growth. One possible explanation for reduced cost growth for communications missions and ground equipment is the prevalence of these technologies in the commercial sector. The widespread use and availability of these types of technologies in both public and private sectors may make these technologies more mature, and thus less risky, than other missions and commodity types. Ground equipment also benefits from the ability to test in an operational environment, a luxury that most space-based systems do not have.

Table 5. DoD Cost Growth Regression Equations

Model Title	Model	Fit	Exclusions
Total Cost Growth	$CG_T = 0.715 - 0.577*(\textit{Communications})$	R^2 0.29 Adj. R^2 0.24	Strategic Missiles and Titan IV
Per Unit Cost Growth Model 1	$CG_U = 0.869 - 0.941*(\textit{Ground Equip}) - 0.661*(\textit{FFP})$	R^2 0.50 Adj. R^2 0.44	None
Per Unit Cost Growth Model 2	$CG_U = 2.069 - 1.178*(\textit{Ground Equip}) - 0.664*(\textit{PM Tenure})$	R^2 0.47 Adj. R^2 0.41	None
Per Unit Cost Growth Model 3	$CG_U = 0.945 - 1.153*(\textit{Ground Equip}) - 0.666*(\textit{FFP})$	R^2 0.56 Adj. R^2 0.49	Strategic Missiles

The study also found firm-fixed price contracts (contracts with a specified payment amount) to be predictive of lower cost growth. This finding is consistent with Rossetti's (2004) finding that firm-fixed price contracts are predictive of reduced support cost growth for DoD weapon systems. However, it is important to remember that regression analysis identifies relationships but does not indicate cause and effect. It could be that firm-fixed price contracts provide contractors with an incentive to minimize cost growth, since additional costs reduce their profit margin. An alternative explanation is that government programs use firm-fixed price contracts on programs that are relatively well defined, have mature technologies, and are less risky. Thus, while the models indicate that firm-fixed price contracts are associated with reduced cost growth, the models do not reveal whether these types of contracts lead to lower cost growth or are deliberately chosen for the types of programs that would be expected to have lower cost growth.

Both the Young Task Force (Defense Science, 2003) and the Government Accountability Office (GAO) (Government, 2006) studies identify high turnover of Program Managers is a factor that contributes to the cost growth of space systems. This study supports this assessment, finding that longer Program Manager tenures are predictive of lower cost growth (and thus, shorter tenures are predictive of higher cost growth). Additionally, this study quantifies the impact of Program Manager tenure, finding that a one year increase in Program Manager tenure is associated with a reduction in per unit cost growth of 66.4 percentage points.

Although a number of DoD weapons systems cost growth studies have found smaller programs to be associated with higher cost growth, this study did not find program size to be predictive of cost growth for space systems.

NASA Predictor Discussion

Cost Growth

Due to the bimodal nature of the cost growth data for the NASA dataset, the inferential analysis began with dividing the dataset into high cost growth and low cost growth programs, and then used logistic regression to assess whether a program was likely to experience high or low cost growth (low cost growth includes no cost growth as well as negative cost growth). Table 6 provides the NASA cost growth models.

Table 6. NASA Cost Growth Regression Equations

Model Title	Model	Fit
High Cost Growth? Logistic Model 1	$L_{HCG} = \frac{e^{2.140 - 0.058*(\textit{Initial Program Size}) + 0.001*(\textit{Total Mass})}}{1 + e^{2.140 - 0.058*(\textit{Initial Program Size}) + 0.001*(\textit{Total Mass})}}$	R^2 (U) 0.57
High Cost Growth? Logistic Model 2	$L_{HCG} = \frac{e^{0.741 - 0.038*(\textit{Initial Program Size}) + 0.001*(\textit{Dry Mass}) + 38.705*(\textit{Microgravity})}}{1 + e^{0.741 - 0.038*(\textit{Initial Program Size}) + 0.001*(\textit{Dry Mass}) + 38.705*(\textit{Microgravity})}}$	R^2 (U) 0.50
High Cost Growth Linear Model	$CG_H = 1.232 + 1.037*(\textit{Space Physics})$	R^2 0.77 Adj. R^2 0.74
Low Cost Growth Linear Model	$CG_L = 0.509 - 0.014*(\textit{Program Start})$	R^2 0.18 Adj. R^2 0.16

From the logistic regression analysis, this study found that larger program size (measured in total cost) decreased the likelihood of being a high cost growth program, whereas more massive spacecrafts and microgravity missions increased the likelihood of being a high cost growth program. This finding of larger programs being associated with lower cost growth is consistent with many other cost growth studies (Schaffer, 2004; McCrillis, 2003; Dameron et al., 2002; Pannell, 1994:42; Drezner et al., 1993:27). As discussed in Chapter II, smaller programs are more likely to experience high cost growth due to minimal oversight and because equivalent costs and increases in costs represent proportionally greater amounts of the total cost for smaller programs (Drezner et al., 1993:49). Further study is recommend to determine the cause of the increased likelihood of high cost growth for more massive spacecraft and microgravity missions. While this increased likelihood could be an indication of the increased technical complexity of these types of systems, it may also be an indication of other problems unique to these programs such as inadequate cost estimating procedures, deficient program acquisition processes, or other technical or scientific issues.

After using the logistic regression to determine the likelihood of high cost growth, the linear regression models are then used for determining the quantity of cost growth. For those programs that are likely to experience high cost growth, the amount of cost growth increases for those programs from a space physics mission. Again, further study is recommended to identify the root causes for this relationship.

For programs in which the logistic models predict to be likely to experience low cost growth, program start date is the best predictor of the amount of cost growth, with more recent programs associated with lower cost growth. Further study is recommended

to determine if this relationship is an indication of improved program acquisition or cost estimating processes.

Schedule Growth

Similar to the cost growth analysis for NASA space systems, the schedule growth dataset also displays a bimodal distribution. Thus, the inferential analysis began with dividing the dataset into high schedule growth and low schedule growth programs, and then used logistic regression to assess whether a program was likely to have high or low schedule growth. After determining whether or not high schedule growth was likely, the linear regression models are then used to determine the amount of likely growth. Table 7 provides the NASA schedule growth models.

Table 7. NASA Schedule Growth Regression Equations

Model Title	Model	Fit
High Schedule Growth? Logistic Model	$L_{HSG} = \dfrac{e^{-2.186\ +\ 0.001*(\textit{Final Program Size})}}{1 + e^{-2.186\ +\ 0.001*(\textit{Final Program Size})}}$	R^2 (U) 0.15
High Schedule Growth Linear Model	$SG_H = 0.899 + 1.188 *(\textit{JPL}) + 0.587 *(\textit{Int'l Develop})$	R^2 0.79 Adj. R^2 0.73
Low Schedule Growth Linear Model	$SG_L = 0.252 + 0.243 *(\textit{Northrop Grumman}) - 0.274 *(\textit{Johns Hopkins})$	R^2 0.27 Adj. R^2 0.23

The logistic regression results found that larger programs (measured in total cost) are more likely to experience high schedule growth. For those programs likely to experience high schedule growth, the linear regressions reveal that those programs

developed by JPL or an International developer (outside of the U.S.) experience a greater amount of schedule growth. For those programs likely to experience low schedule growth, those developed by Northrop Grumman are associated with increased schedule growth, whereas those space systems developed by Johns Hopkins are associated with a reduced amount of schedule growth. Keep in mind that these results do not indicate cause and effect; more research is needed to discover whether these developers have processes that actually lead to schedule growth (or reduced growth in the case of Johns Hopkins) or if they are more likely to take-on complex projects that possess other factors leading to schedule growth.

Interestingly, the study did not find a predictive relationship between cost and schedule growth for NASA space systems; many of the programs that experienced cost growth did not experience schedule growth and vice versa. Note that the study did not find these variables to be negatively correlated either; that is, it does not appear that the programs avoid one type of growth by permitting the other (e.g., increasing costs in order to reduce schedule slip). The finding that these types of growth are not strongly correlated, and thus have different factors influencing each, is consistent with the findings of Foreman (2007) and Drezner and Smith (1990).

Conclusions

This study provides defense and civil cost estimators and space system acquirers with a set of models to aid in predicting cost and schedule growth. Since many of the systems that the defense space acquisition community will be tasked to acquire will be systems other than ground equipment and communications systems, the analysis suggests that cost estimators and acquirers should anticipate that other systems are likely to

experience higher cost growth, and should plan accordingly. Additionally, this research indicates that longer Program Manager tenures are associated with decreased cost growth. The respective model predicts that increasing the average Program Manager tenure by one-year will reduce the anticipated per unit cost growth by 66.4 percentage points. Thus, this research supports the recommendation of Young's Task Force to increase the length of Program Managers' tenures (Defense Science, 2003).

Similarly, while NASA will continue to procure a variety of systems, with wide ranges of program sizes, spacecraft sizes, and mission types, it would behoove cost estimators and acquirers to recognize that smaller programs, more massive spacecraft, and microgravity and space physics missions are more vulnerable to experiencing higher cost growth. Additionally, cost estimators and acquirers should also recognize that while larger programs are less vulnerable to cost growth, they are more vulnerable to schedule growth.

Study Limitations

This study is an exploratory analysis, intended to provide a starting point for developing space system cost and schedule growth models for use by space system acquirers and cost estimators. The study seeks not only to identify the best predictors of cost and schedule growth, but also to identify an appropriate methodology for acquirers and cost estimators to use in establishing their own models. While linear regression analysis is sufficient for DoD space programs, it is not suitable on its own for NASA space systems. Instead, the analysis found that NASA systems have bimodal distributions that are best modeled by first using logistic regression to determine if a program was likely to experience high or low growth, and then using linear regression

models to predict the likely amount of growth. While most of the models are highly predictive, users of the models should keep these limitations in mind:

- This study is a starting point for quantitatively assessing space system cost growth using regression analysis. The models should be further validated with space systems outside of the original dataset. Until this has been accomplished, the models are only known to be predictive of programs within the dataset.
- The study identified a bimodal relationship for cost and schedule growth among NASA programs, however the number of programs belonging to the high cost growth and high schedule growth categories is relatively small. The NASA dataset should be augmented with additional programs to verify this bimodal relationship.
- This study identifies and quantifies those factors that are best predictors of space system cost and schedule growth; however, it does not include the depth of a qualitative study in investigating the root causes of these relationships.
- This study included only DoD Major Defense Acquisition Programs (MDAPs) reported in the Selected Acquisition Report and select NASA spacecraft. The study does not account for commercial space systems, classified space systems, NRO space systems, or non-MDAP programs.
- There are many potential predictors of cost and schedule growth that were not included in the analysis due to the lack of available data. Potential predictors not evaluated include: schedule milestones, number of requirements and requirements changes, amount of systems engineering expertise, and level of technology maturity.

- The models can only be as sound as the data from which they are derived. Inconsistencies in data format such as which costs are included in the total figure, the level of technology maturity when the program was initiated, and the combination or division of multiple satellites into a single or several programs, all affect the accuracy of the models.
- The study also includes some assumptions for the inflation and quantity adjustments. For example, when adjusting DoD *Total Cost Growth* for quantity, the current estimate was adjusted by omitting the Quantity Variance category from the SAR. This assumes that all cost growth related to quantity is captured in this category. With the NASA datasets, the final cost was adjusted for inflation by assuming that all costs were in then year dollars for the launch year rather than breaking the costs down by each year they were incurred and adjusting each year for inflation separately. It was assumed that the bulk of funds are spent at the tail end of the program and that assuming all costs were incurred during the launch year would be a close approximation. While the inflation and quantity adjustments are not perfect, they better capture reality than if no adjustments were made at all.

Recommendations for Future Research

From this study stems numerous avenues for further research. Potential future areas for study include:

- Test models provided herein with additional data from other NASA and DoD programs to validate models or establish more robust models,

- Test models provided herein using data from commercial and classified systems to see if the models apply or if new models are needed,
- Explore additional predictor variables not evaluated herein, such as requirements, systems engineering expertise, or technological maturity,
- Augment NASA data with additional space programs to see if the bimodal distributions for cost and schedule growth hold, or
- Further explore relationships identified herein using a more in-depth qualitative analysis.

Chapter Summary

This study provides a foundation for predicting space system cost and schedule growth. It explored numerous programmatic characteristics to identify those that are best predictors of growth. The study provides four models for use in predicting DoD space system cost growth. It also identified a bimodal distribution for cost and schedule growth of NASA space systems, and thus established a series of logistic and linear models to assist in cost and schedule growth forecasting for NASA space systems.

Appendix A. List of DoD Space Systems

System Name	Initial Selected Acquisition Report (SAR)	Description
Advanced Extremely High Frequency (AEHF)	2002	Satellite
Evolved Expendable Launch Vehicle (EELV)	1999	Launch Vehicle
Global Broadcast Service (GBS)	1997	Ground Equipment
Minuteman III Guidance Replacement Program (GRP)	1993	Strategic Missile Upgrade
Minuteman III Propulsion Replacement Program (PRP)	1996	Strategic Missile Upgrade
NAVSTAR Global Positioning System (GPS)	1980	Satellite
NAVSTAR Global Positioning System (GPS) Equipment	1980	Ground Equipment
National Polar-orbiting Operational Environmental Satellite System (NPOESS)	2002	Satellite
Space-Based Infrared System (SBIRS) High	1997	Satellite
Wideband Global SATCOM (WGS)	2001	Satellite
Mobile User Objective System (MUOS)	2004	Satellite
Defense Satellite Communication System (DSCS) III	1977	Satellite
Defense Support Program (DSP)	1983	Satellite
Inertial Upper Stage (IUS)	1982	Launch Vehicle Upper Stage
Peacekeeper	1983	Strategic Missile
Titan IV	1985	Launch Vehicle
Minuteman II	1969	Strategic Missile
Minuteman III	1969	Strategic Missile
Defense Meteorological Satellite Program (DMSP)	1983	Satellite
MILSTAR	1992	Satellite
Single Channel Anti-jam Man-Portable Terminal (SCAMP)	1992	Ground Equipment

Appendix B. List of NASA Space Systems

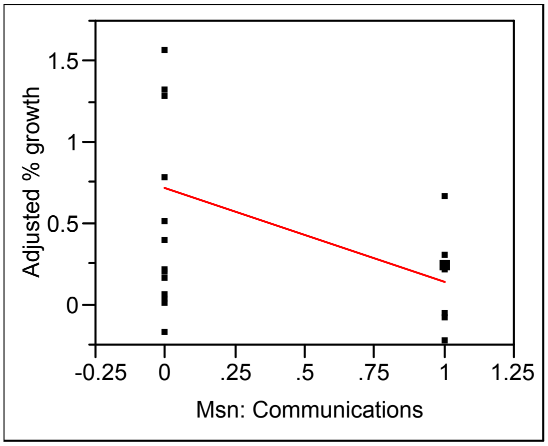
Program Name	Initial budget year	Launch Date	Full Name
ACE	1994	Aug-97	Advanced Composition Explorer Satellite
ACTS	1983	Sep-93	Advanced Communications Technology Satellite
AE-C	1971	Dec-73	Atmosphere Explorer-C
AEM-HCMM	1974	Apr-78	Application Explorer Mission-Heat Capacity Mapping Mission
ATS-1	Not Available	Dec-66	Applications Technology Satellite 1
ATS-2	Not Available	Apr-67	Applications Technology Satellite 2
ATS-5	Not Available	Aug-69	Applications Technology Satellite 5
ATS-6	1968	May-74	Applications Technology Satellite 6
Aura	1993	Jul-04	Aura
AXAF	1990	Jul-99	(Chandra) Advanced X-Ray Astrophysics Facility
CALIPSO	1999	Apr-06	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
Cassini	1990	Oct-97	Cassini
CloudSat	1999	Apr-06	CloudSat
COBE	1982	Nov-89	Cosmic Background Explorer
CONTOUR	2000	Jul-02	Comet Nucleus Tour
COSTR	1987	Jul-92	Collaborative Solar Terrestrial Research
Deep Space 1	1996	Oct-98	Deep Space 1
DSCS-2	1969	Nov-71	Defense Satellite Communications System
Endeavour	1987	May-92	Shuttle Orbiter Endeavour (OV-105)
EO-1	1996	Nov-00	Earth Observing One
ESSP (VCL/GRACE)	1997	Mar-02	Earth Systems Science Pathfinder (Vegetation Canopy Lidar/Gravity Recovery and Climate Experiment)
EUVE	1984	Jun-92	Extreme Ultraviolet Explorer
FAST	1989	Aug-96	Fast Auroral Snapshot Explorer
FUSE	1995	Jun-99	Far Ultraviolet Spectroscopic Explorer
GALEX	1998	Apr-03	Galaxy Evolution Explorer
Galileo	1978	Oct-89	Galileo
Genesis	1998	Aug-01	Genesis
GOES I-M	1984	Apr-94	Geostationary Operational Environmental Satellite

GRO	1981	Apr-91	(Compton) Gamma Ray Observatory
HEAO-A	1972	Aug-77	High Energy Astronomical Observatory
HESSI	1998	Feb-02	High Energy Solar Spectroscopic Imager (now RHESSI)
HETE-II	1997	Oct-00	High Energy Transient Experiment/Explorer
HST	1977	Apr-90	Hubble Space Telescope
ICESat	1996	Jan-03	Ice, Clouds and Land Elevation Satellite
IMAGE	1996	Mar-00	Imager for Magnetopause to Aurora Global Exploration
LANDSAT-A	1969	Jul-72	Land Remote Sensing Satellite
LANDSAT-D	1977	Jul-82	Land Remote Sensing Satellite
Lunar Orbiter	1964	Aug-66	Lunar Orbiter
Lunar Prospector	1996	Jan-98	Lunar Prospector Orbiter
Magellan	1984	May-89	Magellan
MAP	1996	Jun-01	(Wilkinson) Microwave Anisotropy Probe
Mars Observer	1985	Sep-92	Mars Observer
Mars Odyssey	1998	Apr-01	Mars Odyssey
Mars Pathfinder	1994	Dec-96	Mars Pathfinder
MCO	1996	Dec-98	Mars Climate Orbiter
MER	2000	Jun-03	Mars Exploration Rover
MGS	1994	Nov-96	Mars Global Surveyor
NEAR	1994	Feb-96	Near Earth Asteroid Rendezvous (Shoemaker)
NSCAT	1985	Aug-96	NASA Scatterometer
OSO-8	1970	Jun-75	Orbiting Solar Observatory
SCATHA	1976	Jan-79	Spacecraft Charging at High Altitudes
SIRTF	1996	Aug-03	(Spitzer) Space Infrared Telescope Facility
Skylab Workshop	1969	May-73	Skylab Workshop
SMS-1	1970	May-74	Synchronized Meteorology Satellite
SORCE	1999	Jan-03	Solar Radiation and Climate Experiment
Space Station	1987	Nov-98	International Space Station Alpha (ISSA)
Spacelab	1974	Nov-83	Spacelab
STARDUST	1996	Feb-99	Star Dust

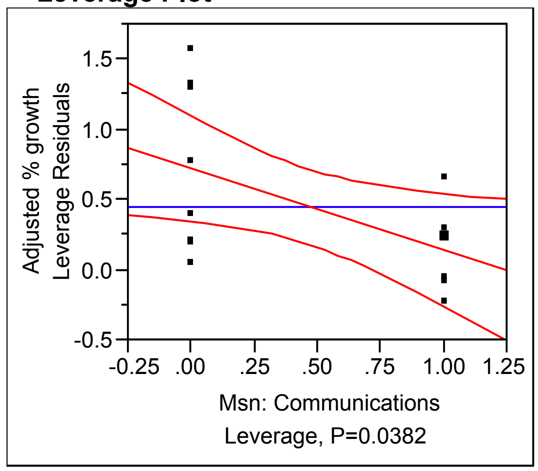
SWAS/TRACE/WIRE	1989	Apr-98	Submillimeter Wave Astronomy Satellite/Transition Region and Coronal Explorer/Wide-Field Infrared Explorer
TDRSS replen	1994	Jun-00	Tracking and Data Relay Satellite - 3 replenishment satellites
TDRSS-7	1986	Jul-95	Tracking and Data Relay Satellite
Terra	1991	Dec-99	EOS AM-1
TIMED	1997	Dec-01	Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics
TIROS-M	Not Available	Jan-70	Television Infrared Observation Satellite (also ITOS-1)
TOPEX	1987	Aug-92	Ocean Topography Experiment/Poseidon
TRMM	1991	Nov-97	Tropical Rainfall Measuring Mission
TSS	1984	Jul-92	Tethered Satellite System
UARS	1982	Sep-91	Upper Atmosphere Research Satellite
Ulysses	1979	Oct-90	Ulysses
Viking Lander	1970	Aug-75	Viking Lander
XTE	1990	Dec-95	(Rossi) X-Ray Timing Explorer

Appendix C. DoD Total Cost Growth Linear Regression Model Output

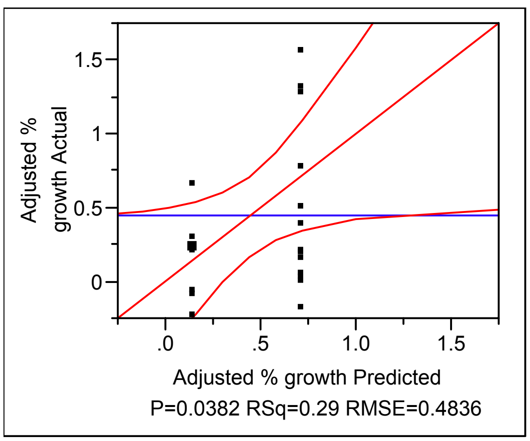
Whole Model
Regression Plot



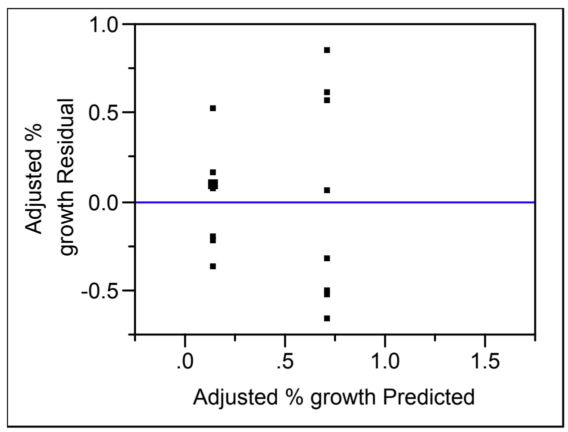
Msn: Communications
Leverage Plot



Actual by Predicted Plot



Residual by Predicted Plot



Summary of Fit

RSquare	0.290373
RSquare Adj	0.235787
Root Mean Square Error	0.483612
Mean of Response	0.445538
Observations (or Sum Wgts)	15

Analysis of Variance

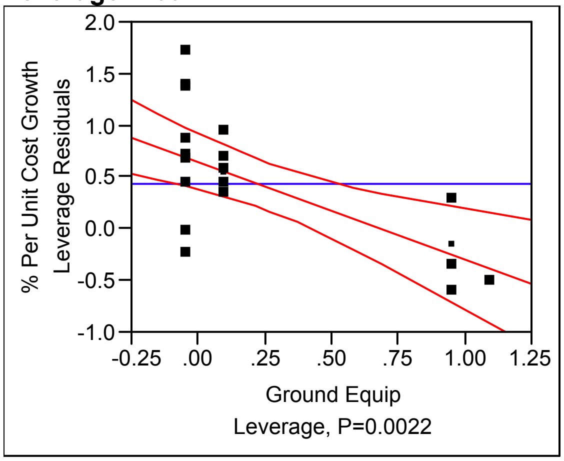
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1.2441269	1.24413	5.3195
Error	13	3.0404483	0.23388	Prob > F
C. Total	14	4.2845752		0.0382

Parameter Estimates

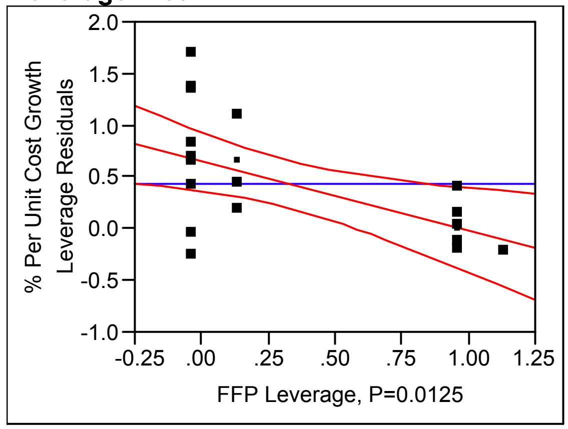
Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.7149335	0.170983	4.18	0.0011	0		
Msn: Communications	-0.577277	0.250293	-2.31	0.0382	-0.53886	0	1

Appendix D. DoD Per Unit Cost Growth Linear Regression Model 1 Output

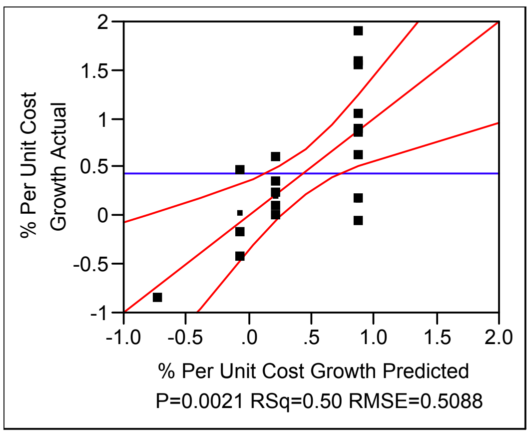
Ground Equip
Leverage Plot



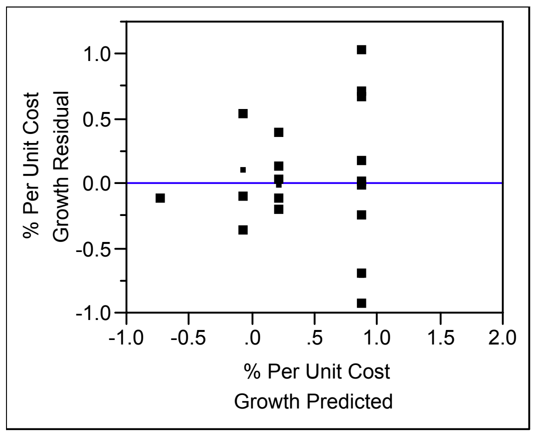
FFP
Leverage Plot



Whole Model
Actual by Predicted Plot



Residual by Predicted Plot



Summary of Fit

RSquare	0.496146
RSquare Adj	0.440163
Root Mean Square Error	0.508769
Mean of Response	0.424743
Observations (or Sum Wgts)	21

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4.5879632	2.29398	8.8623
Error	18	4.6592316	0.25885	Prob > F
C. Total	20	9.2471948		0.0021

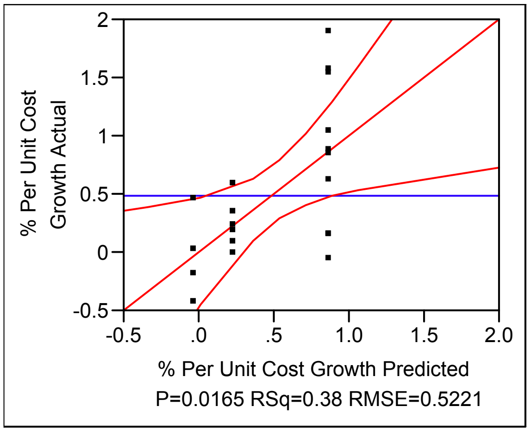
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.8693884	0.155493	5.59	<.0001	0		
Ground Equip	-0.941423	0.263987	-3.57	0.0022	-0.60425	0	1
FFP	-0.661491	0.238515	-2.77	0.0125	-0.46992	0	1

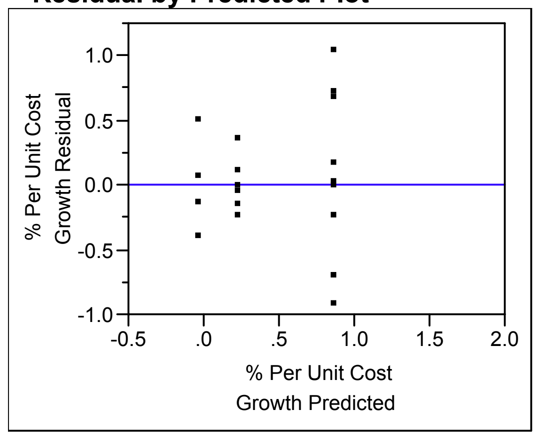
Appendix E. DoD Per Unit Cost Growth Linear Regression Model 1 Output: Excludes GPS User Equipment

Whole Model

Actual by Predicted Plot

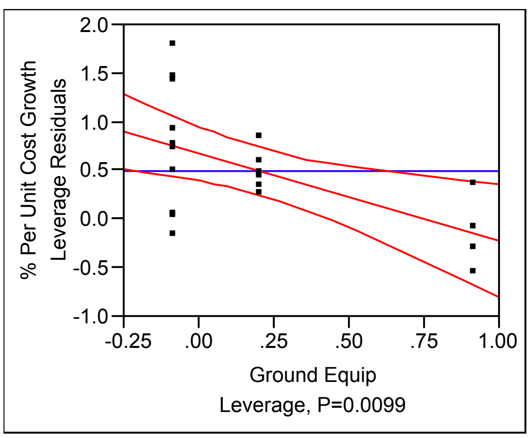


Residual by Predicted Plot



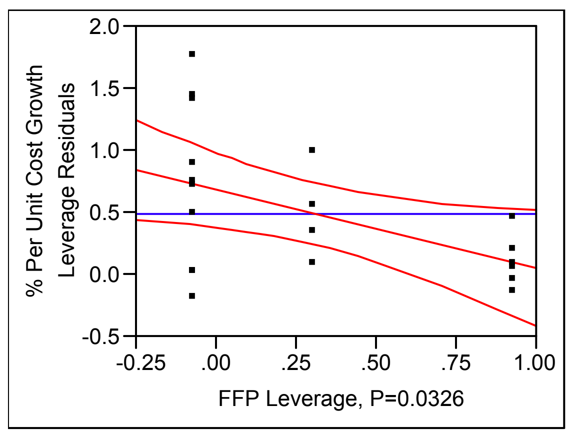
Ground Equip

Leverage Plot



FFP

Leverage Plot



Summary of Fit

RSquare	0.382844
RSquare Adj	0.310237
Root Mean Square Error	0.522114
Mean of Response	0.489074
Observations (or Sum Wgts)	20

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	2.8747826	1.43739	5.2728
Error	17	4.6342448	0.27260	Prob > F
C. Total	19	7.5090275		0.0165

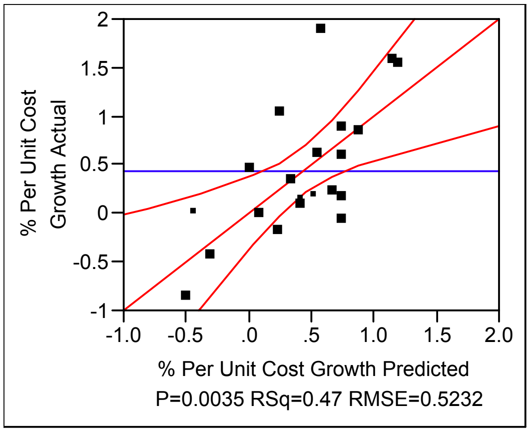
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.856553	0.165107	5.19	<.0001	0		
Ground Equip	-0.896499	0.308887	-2.90	0.0099	-0.58524	0	1
FFP	-0.627263	0.269618	-2.33	0.0326	-0.46912	0	1

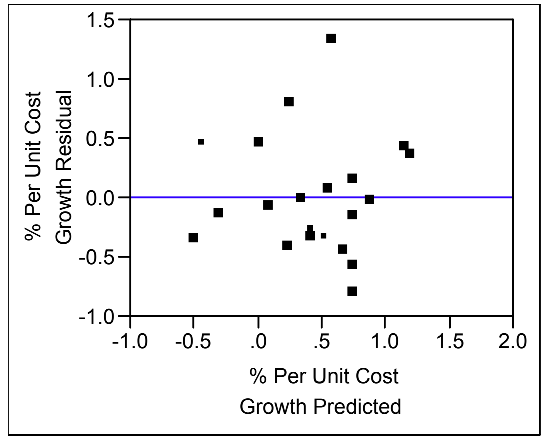
Appendix F. DoD Per Unit Cost Growth Linear Regression Model 2 Output

Whole Model

Actual by Predicted Plot

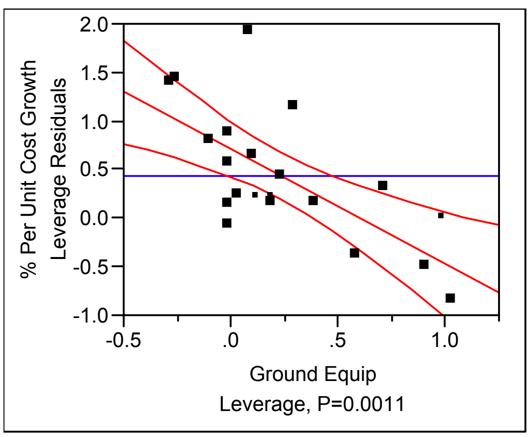


Residual by Predicted Plot



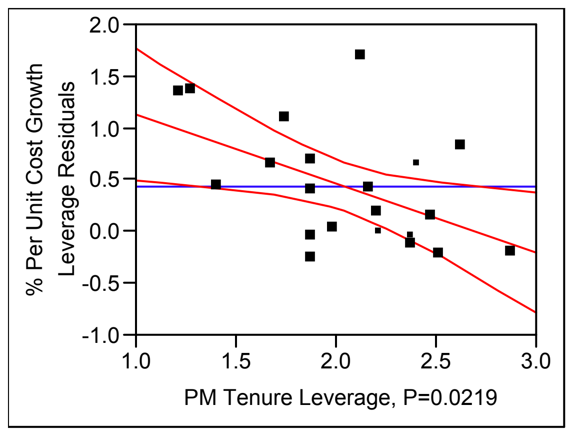
Ground Equip

Leverage Plot



PM Tenure

Leverage Plot



Summary of Fit

RSquare	0.467177
RSquare Adj	0.407974
Root Mean Square Error	0.523191
Mean of Response	0.424743
Observations (or Sum Wgts)	21

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4.3200722	2.16004	7.8911
Error	18	4.9271226	0.27373	Prob > F
C. Total	20	9.2471948		0.0035

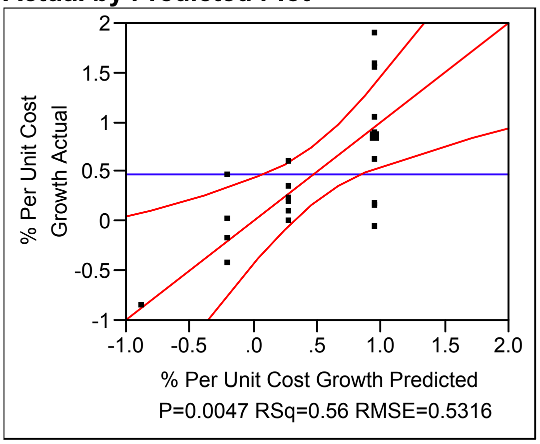
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	2.0692045	0.591726	3.50	0.0026	0		
Ground Equip	-1.177888	0.302594	-3.89	0.0011	-0.75602	0	1
PM Tenure	-0.664477	0.264845	-2.51	0.0219	-0.48728	1	3

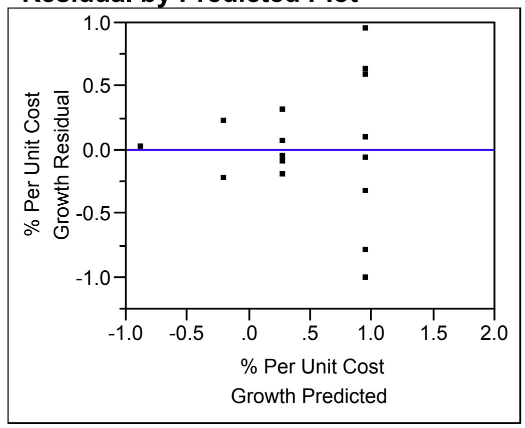
Appendix G. DoD Per Unit Cost Growth Linear Regression Model 3 Output: Excludes Strategic Missiles

Whole Model

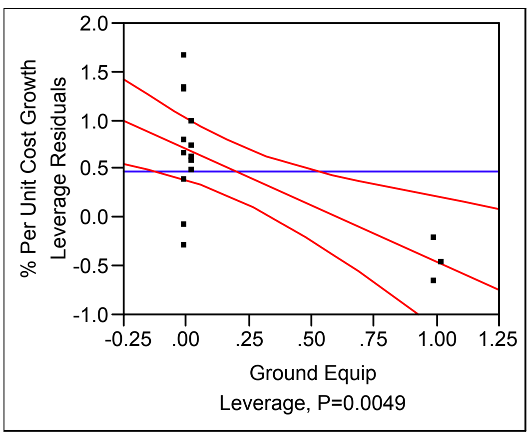
Actual by Predicted Plot



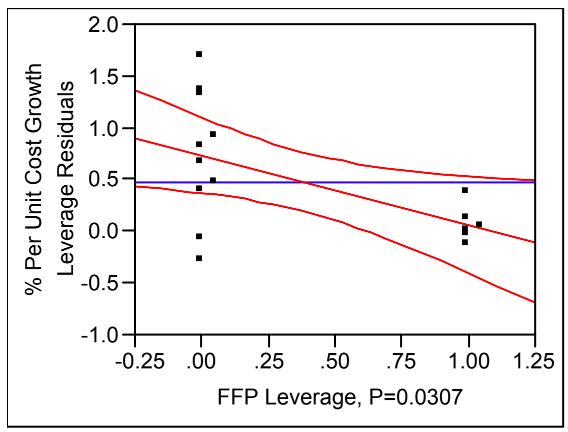
Residual by Predicted Plot



Ground Equip
Leverage Plot



FFP
Leverage Plot



Summary of Fit

RSquare	0.561866
RSquare Adj	0.49446
Root Mean Square Error	0.531616
Mean of Response	0.479506
Observations (or Sum Wgts)	16

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4.7115613	2.35578	8.3356
Error	13	3.6740053	0.28262	Prob > F
C. Total	15	8.3855666		0.0047

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.9453955	0.181404	5.21	0.0002	0		
Ground Equip	-1.153119	0.340798	-3.38	0.0049	-0.6217	0	1
FFP	-0.665813	0.27476	-2.42	0.0307	-0.44525	0	1

Appendix H. NASA Cost Growth Logistic Regression Model 1 Output

Whole Model Test

Model	-LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	10.683222	2	21.36644	<.0001
Full	8.153711			
Reduced	18.836933			
RSquare (U)		0.5671		
Observations (or Sum Wgts)		54		

Converged by Gradient

Lack Of Fit

Source	DF	-LogLikelihood	ChiSquare
Lack Of Fit	51	8.1537110	16.30742
Saturated	53	0.0000000	Prob>ChiSq
Fitted	2	8.1537110	1.0000

Parameter Estimates

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq	Min Value	Max Value
Intercept	-2.139853	1.5549805	1.89	0.1688		
Initial Program Size (Original Estimate CY07)	0.05798487	0.0265758	4.76	0.0291	9.9	27802
Total Mass (kg)	-0.001285	0.0006474	3.94	0.0472	124	109000

For log odds of 0/1

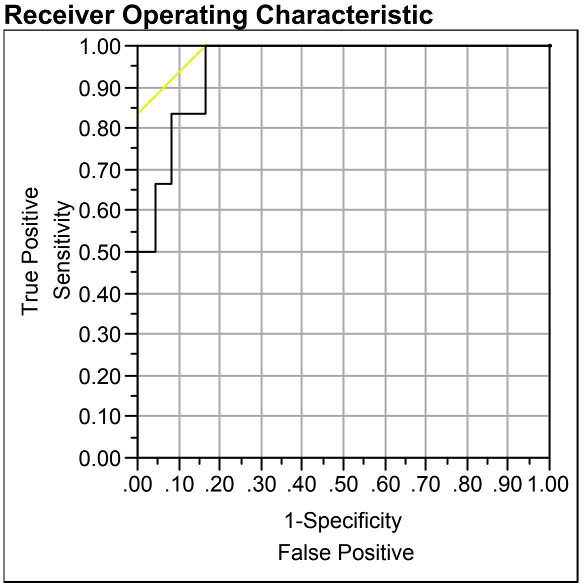
Effect Wald Tests

Source	Nparm	DF	Wald ChiSquare	Prob>ChiSq
Initial Program Size (Original Estimate CY07)	1	1	4.7605558	0.0291
Total Mass (kg)	1	1	3.93933688	0.0472

Effect Likelihood Ratio Tests

Source	Nparm	DF	L-R ChiSquare	Prob>ChiSq
Initial Program Size (Original Estimate CY07)	1	1	21.3478893	<.0001
Total Mass (kg)	1	1	14.0306169	0.0002

Receiver Operating Characteristic



Using High Cost Growth?='1' to be the positive level
Area Under Curve = 0.95139

Appendix I. NASA Cost Growth Logistic Regression Model 2 Output

Whole Model Test

Model	-LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	13.238856	3	26.47771	<.0001
Full	13.049413			
Reduced	26.288270			
RSquare (U)		0.5036		
Observations (or Sum Wgts)		66		

Converged by Gradient

Lack Of Fit

Source	DF	-LogLikelihood	ChiSquare
Lack Of Fit	62	13.049413	26.09883
Saturated	65	0.000000	Prob>ChiSq
Fitted	3	13.049413	1.0000

Parameter Estimates

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq	Min Value	Max Value
Intercept	-0.7413099	1.0158722	0.53	0.4656		
Initial Program Size (Original Estimate CY07)	0.03752431	0.0166158	5.10	0.0239	9.9	27802
Dry Mass (kg)	-0.0008909	0.0003625	6.04	0.0140	117	90607
Msn: Microgravity	-38.705311	83316.394	0.00	0.9996	0	1

For log odds of 0/1

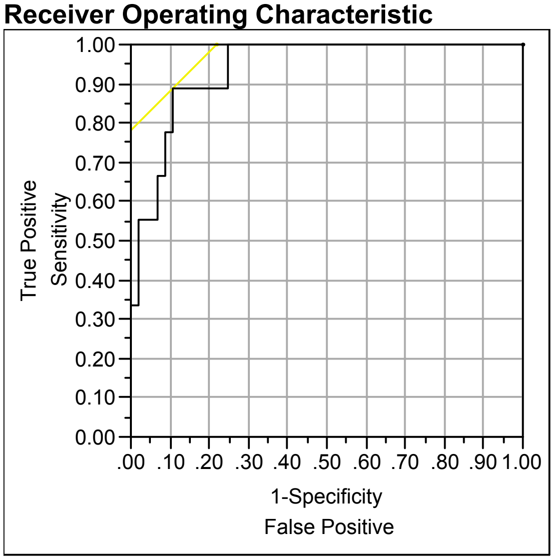
Effect Wald Tests

Source	Nparm	DF	Wald ChiSquare	Prob>ChiSq
Initial Program Size (Original Estimate CY07)	1	1	5.10013649	0.0239
Dry Mass (kg)	1	1	6.03971535	0.0140
Msn: Microgravity	1	1	2.15814e-7	0.9996

Effect Likelihood Ratio Tests

Source	Nparm	DF	L-R ChiSquare	Prob>ChiSq
Initial Program Size (Original Estimate CY07)	1	1	23.2927602	<.0001
Dry Mass (kg)	1	1	17.3608073	<.0001
Msn: Microgravity	1	1	9.25815588	0.0023

Receiver Operating Characteristic

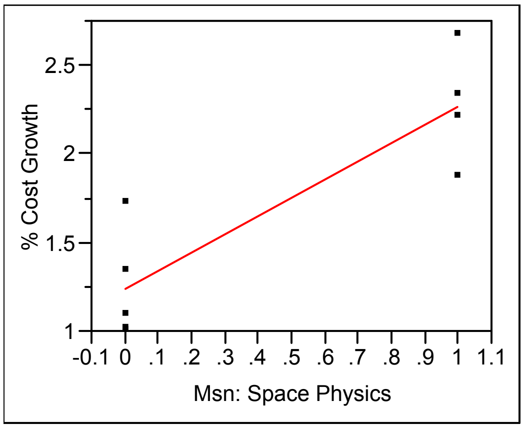


Using High Cost Growth?='1' to be the positive level
Area Under Curve = 0.93957

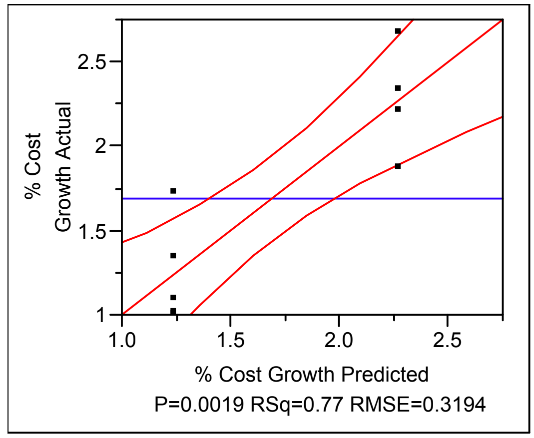
Appendix J. NASA High Cost Growth Linear Regression Model Output

Whole Model

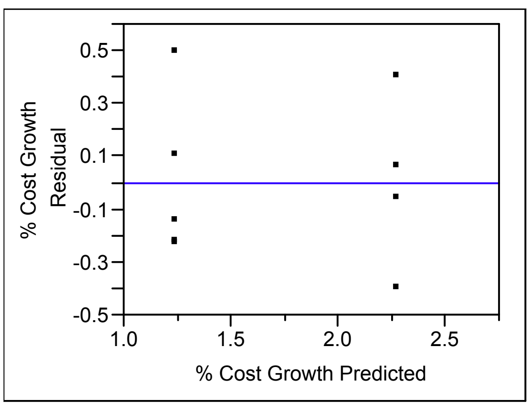
Regression Plot



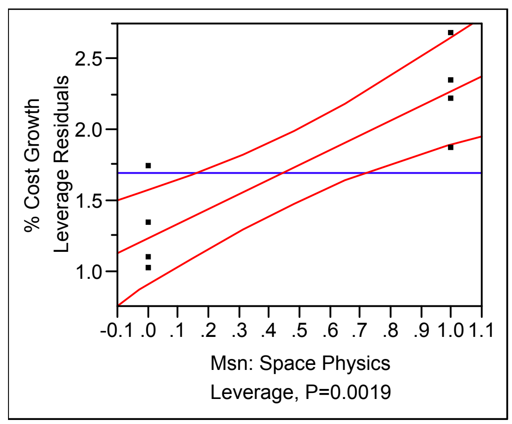
Actual by Predicted Plot



Residual by Predicted Plot



Msn: Space Physics Leverage Plot



Summary of Fit

RSquare	0.769929
RSquare Adj	0.737061
Root Mean Square Error	0.319372
Mean of Response	1.69328
Observations (or Sum Wgts)	9

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	2.3893554	2.38936	23.4253
Error	7	0.7139911	0.10200	Prob > F
C. Total	8	3.1033465		0.0019

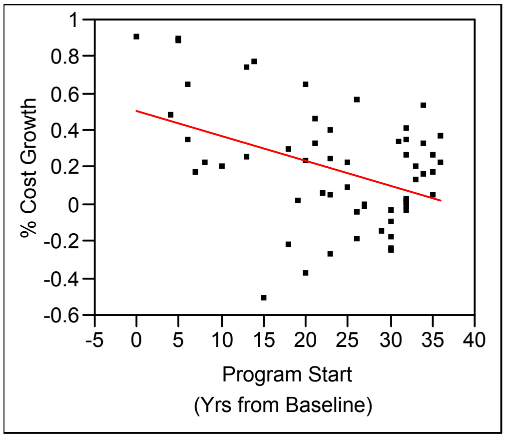
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	1.2324251	0.142828	8.63	<.0001	0		
Msn: Space Physics	1.0369233	0.214242	4.84	0.0019	0.877456	0	1

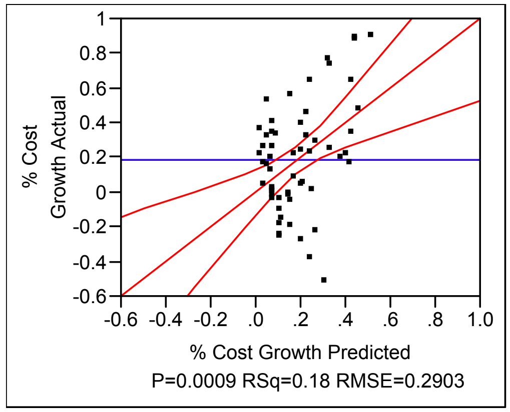
Appendix K. NASA Low Cost Growth Linear Regression Model Output

Whole Model

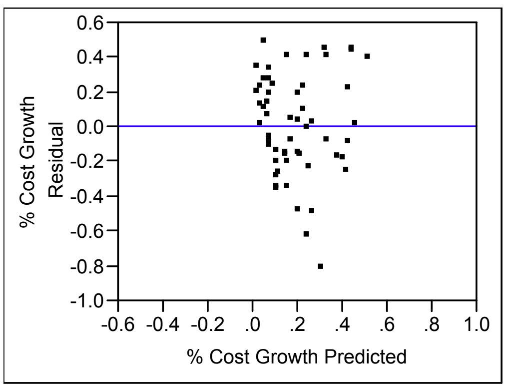
Regression Plot



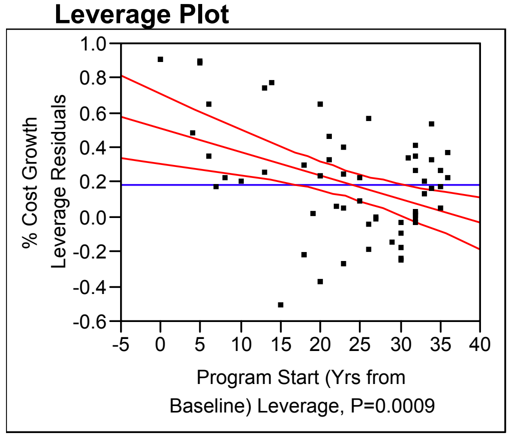
Actual by Predicted Plot



Residual by Predicted Plot



Program Start (Yrs from Baseline) Leverage Plot



Summary of Fit

RSquare	0.179217
RSquare Adj	0.16456
Root Mean Square Error	0.290302
Mean of Response	0.187642
Observations (or Sum Wgts)	58

Analysis of Variance

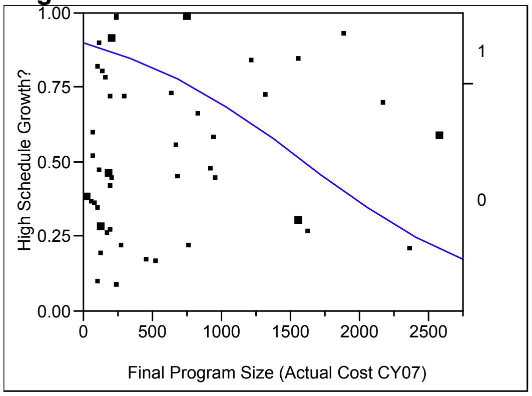
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1.0304816	1.03048	12.2276
Error	56	4.7194180	0.08428	Prob > F
C. Total	57	5.7498996		0.0009

Parameter Estimates

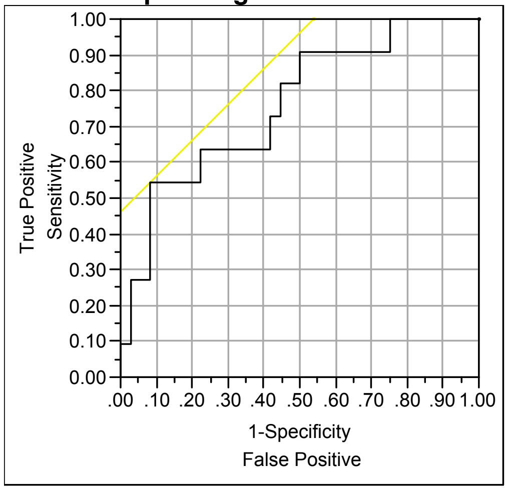
Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.50853	0.099368	5.12	<.0001	0		
Program Start (Yrs from Baseline)	-0.013585	0.003885	-3.50	0.0009	-0.42334	0	36

Appendix L. NASA Schedule Growth Logistic Regression Model Output

Logistic Plot



Receiver Operating Characteristic



Using High Schedule Growth?='1' to be the positive level
Area Under Curve = 0.76010

Whole Model Test

Model	-LogLikelihood	DF	ChiSquare	Prob>ChiSq
Difference	3.747015	1	7.49403	0.0062
Full	21.826393			
Reduced	25.573407			

RSquare (U)	0.1465
Observations (or Sum Wgts)	47

Converged by Gradient

Lack Of Fit

Source	DF	-LogLikelihood	ChiSquare
Lack Of Fit	44	21.826393	43.65279
Saturated	45	0.000000	Prob>ChiSq
Fitted	1	21.826393	0.4864

Parameter Estimates

Term	Estimate	Std Error	ChiSquare	Prob>ChiSq	Min Value	Max Value
Intercept	2.18565739	0.5739752	14.50	0.0001		
Final Program Size (Actual Cost CY07)	-0.0013652	0.0005352	6.51	0.0107	23	38589

For log odds of 0/1

Effect Wald Tests

Source	Nparm	DF	Wald ChiSquare	Prob>ChiSq
Final Program Size (Actual Cost CY07)	1	1	6.50744631	0.0107

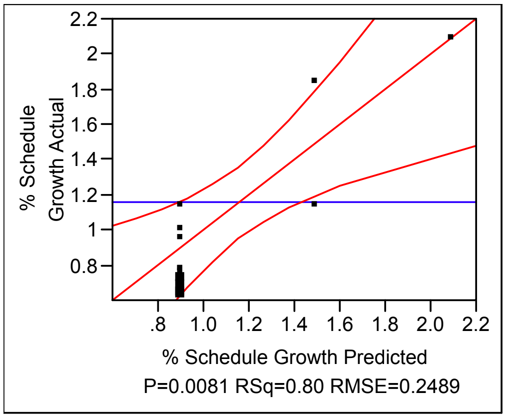
Effect Likelihood Ratio Tests

Source	Nparm	DF	L-R ChiSquare	Prob>ChiSq
Final Program Size (Actual Cost CY07)	1	1	7.4940299	0.0062

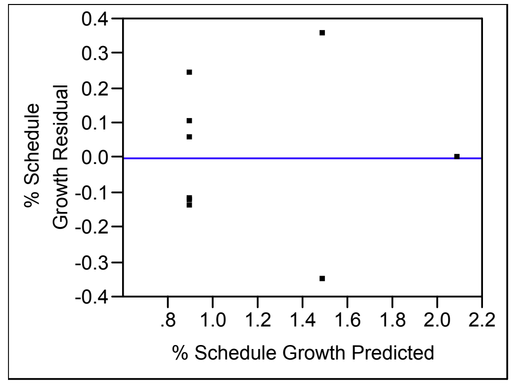
Appendix M. NASA High Schedule Growth Linear Regression Model Output

Whole Model

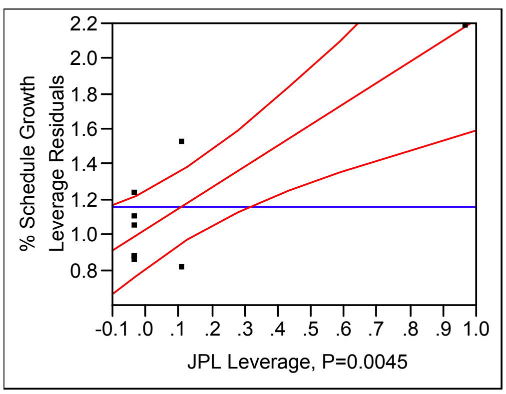
Actual by Predicted Plot



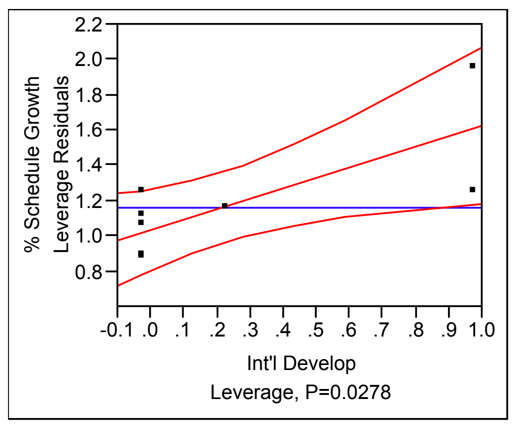
Residual by Predicted Plot



JPL
Leverage Plot



Int'l Develop
Leverage Plot



Summary of Fit

RSquare	0.799249
RSquare Adj	0.732332
Root Mean Square Error	0.24891
Mean of Response	1.161566
Observations (or Sum Wgts)	9

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	1.4799994	0.740000	11.9439
Error	6	0.3717381	0.061956	Prob > F
C. Total	8	1.8517375		0.0081

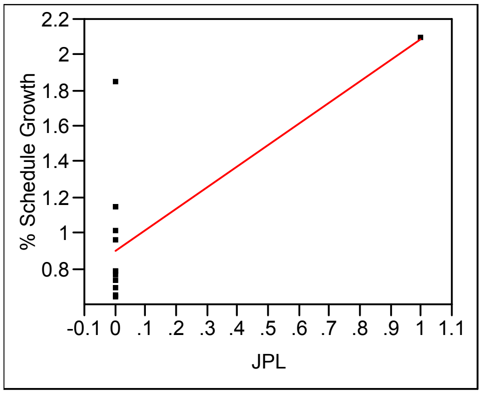
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.899177	0.101617	8.85	0.0001	0		
JPL	1.1877795	0.268854	4.42	0.0045	0.822943	0	1
Int'l Develop	0.5868608	0.203234	2.89	0.0278	0.537883	0	1

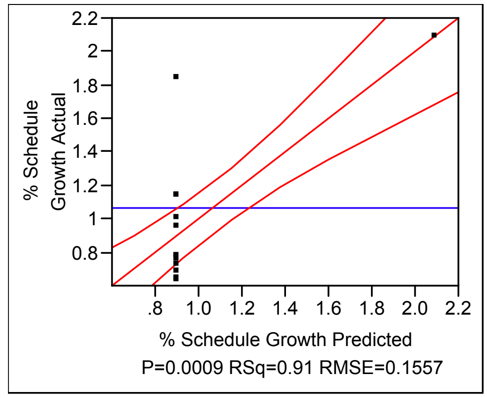
Appendix N. NASA High Schedule Growth Linear Regression Model Output: Two Influential Data Points Removed

Whole Model

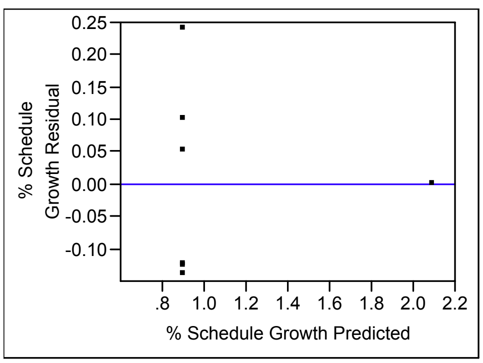
Regression Plot



Actual by Predicted Plot

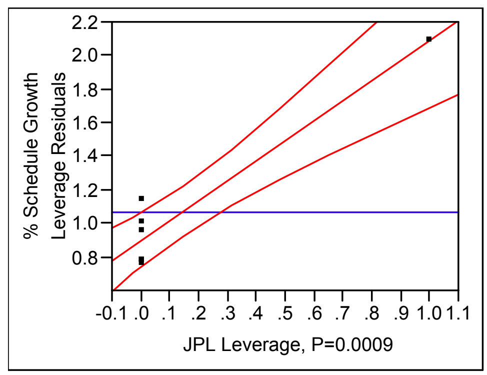


Residual by Predicted Plot



JPL

Leverage Plot



Summary of Fit

RSquare	0.908932
RSquare Adj	0.890719
Root Mean Square Error	0.155666
Mean of Response	1.06886
Observations (or Sum Wgts)	7

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1.2092745	1.20927	49.9042
Error	5	0.1211595	0.02423	Prob > F
C. Total	6	1.3304340		0.0009

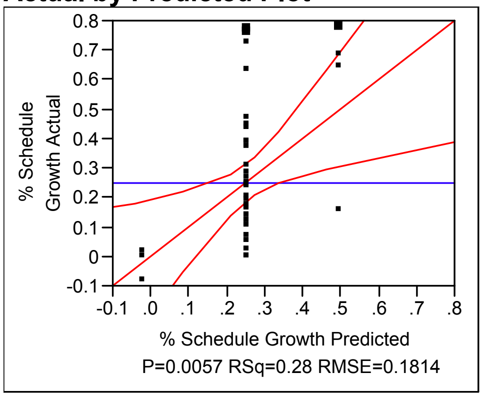
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.899177	0.06355	14.15	<.0001	0		
JPL	1.1877795	0.168138	7.06	0.0009	0.953379	0	1

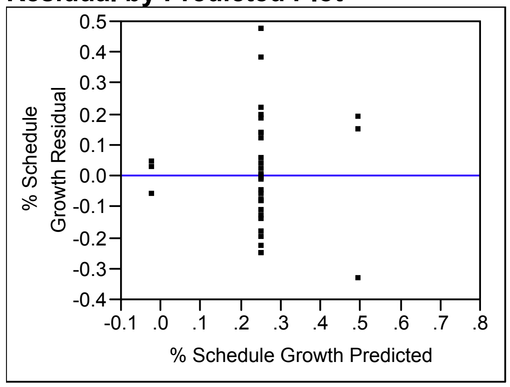
Appendix O. NASA Low Schedule Growth Linear Regression Model Output

Whole Model

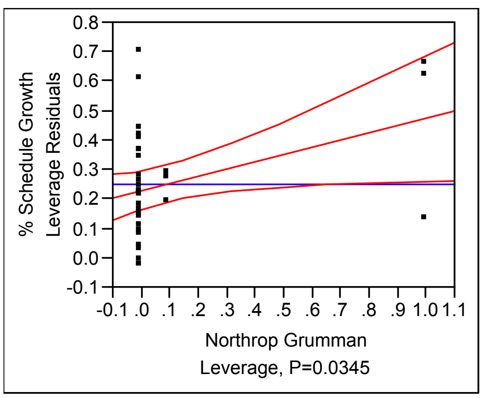
Actual by Predicted Plot



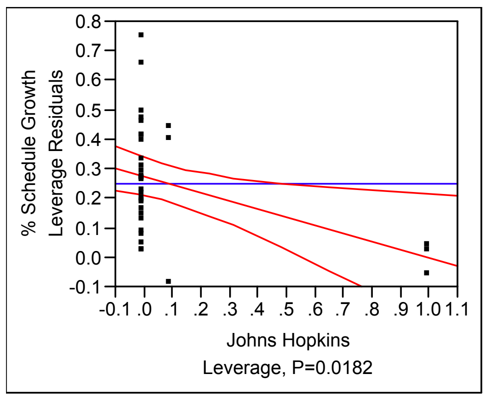
Residual by Predicted Plot



Northrop Grumman
Leverage Plot



Johns Hopkins
Leverage Plot



Summary of Fit

RSquare	0.276105
RSquare Adj	0.230861
Root Mean Square Error	0.181377
Mean of Response	0.249582
Observations (or Sum Wgts)	35

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.4015266	0.200763	6.1026
Error	32	1.0527272	0.032898	Prob > F
C. Total	34	1.4542538		0.0057

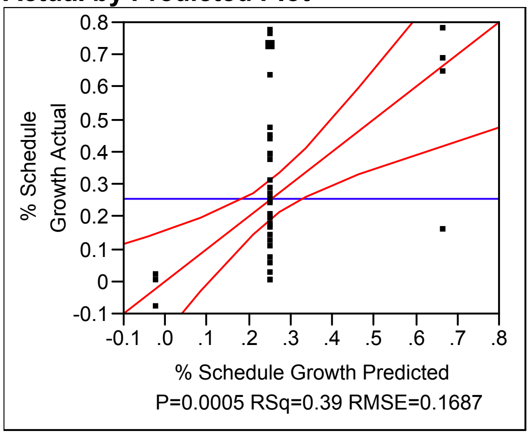
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.252222	0.033681	7.49	<.0001	0		
Northrop Grumman	0.2429117	0.110001	2.21	0.0345	0.333603	0	1
Johns Hopkins	-0.27371	0.110001	-2.49	0.0182	-0.3759	0	1

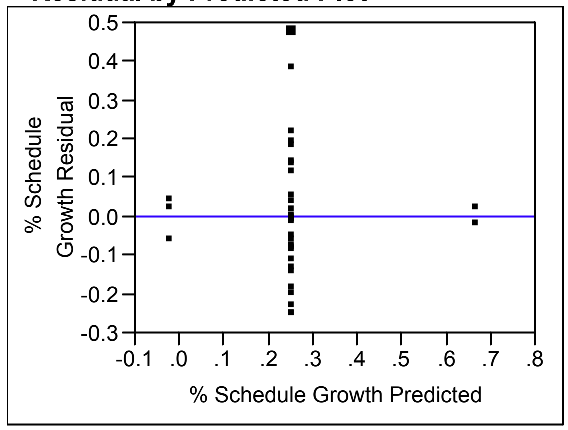
Appendix P. NASA Low Schedule Growth Linear Regression Model Output: Influential Data Point Removed

Whole Model

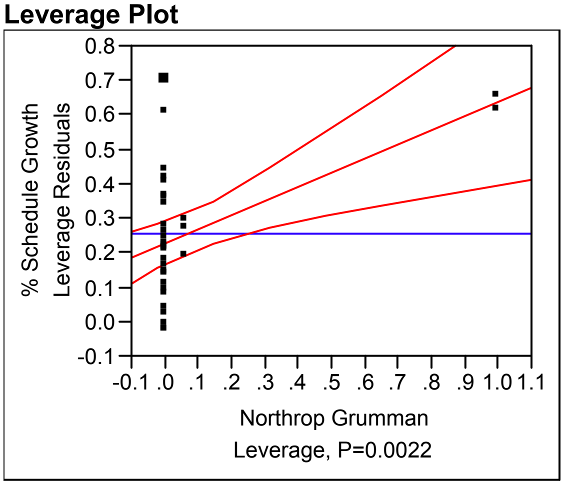
Actual by Predicted Plot



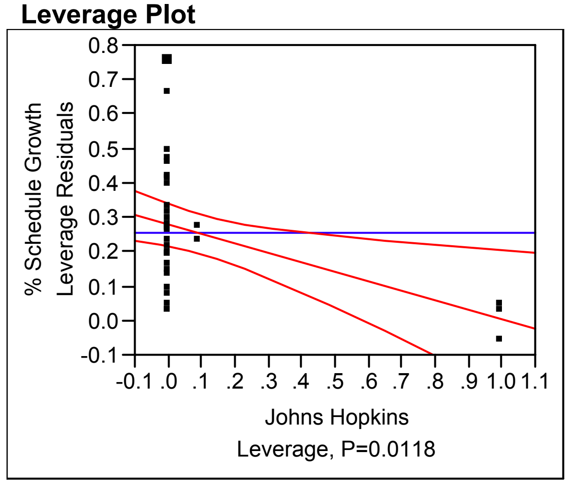
Residual by Predicted Plot



Northrop Grumman Leverage Plot



Johns Hopkins Leverage Plot



Summary of Fit

RSquare	0.389509
RSquare Adj	0.350123
Root Mean Square Error	0.168731
Mean of Response	0.252266
Observations (or Sum Wgts)	34

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	0.5631070	0.281554	9.8894
Error	31	0.8825755	0.028470	Prob > F
C. Total	33	1.4456826		0.0005

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	Min Value	Max Value
Intercept	0.252222	0.031333	8.05	<.0001	0		
Northrop Grumman	0.4113118	0.123356	3.33	0.0022	0.469337	0	1
Johns Hopkins	-0.27371	0.102332	-2.67	0.0118	-0.37649	0	1

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
27-03-2008	Master's Thesis	Jun 2007 - Mar 2008

4. TITLE AND SUBTITLE
Predicting Cost and Schedule Growth for Military and Civil Space Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Rusnock, Christina, F., First Lieutenant, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way, WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GRD/ENC/08M-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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Space and Missile Systems Center, Financial Management Division (SMC/FMC)
483 N. Aviation Blvd.
Los Angeles, CA 90245-2808
DSN: 633-2485

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research seeks to identify factors contributing to military and civil space system cost and schedule growth, quantify the relative impact of these factors, and establishing a set of models for predicting cost and schedule growth. The analysis consists of logistic and multiple regression to assess 21 Department of Defense and 71 National Aeronautics and Space Administration (NASA) space programs. The study finds that, for military spaces systems, communications missions, ground equipment, firm-fixed price contracts, and increased program manager tenure are all predictive of lower cost growth. For NASA space programs, the study finds that smaller programs (by total cost), more massive spacecraft, microgravity missions, and space physics missions are predictive of higher cost growth. For schedule growth of NASA programs, the study finds that larger programs and those developed by the Jet Propulsion Laboratory, Northrop Grumman, or international developers are predictive of increased schedule growth, whereas those programs developed by Johns Hopkins University are predictive of reduced schedule growth.

15. SUBJECT TERMS
Multiple Regression, Logistic Regression, Cost Growth, Schedule Growth, Space Systems, Space Programs, DoD, DoD Acquisition, NASA, NASA Acquisition, SAR, Selected Acquisition Report, Space System Cost Growth, Space System Schedule Growth, Inferential Statistics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU	145	Dr. Edward D. White III
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